aerial photographic TECHNIQUES

FOR ESTIMATING DAMAGE BY INSECTS IN WESTERN FORESTS

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The aerial photo shows tree killing by the Douglas-fir beetle as it appears on Ektachrome Aero color film

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INTRODUCTION

A manager responsible for administering forest lands needs to keep a constant check on the status of the forest resource and the changes that have taken place, or are likely to take place. Among the many kinds of information he needs is that on the damage caused by forest insects. Such knowledge may affect his decisions on the amount of allowable cut, his plans for the orderly harvest of timber, the salvage of dead or damaged material, and the control of insect outbreaks.

Keeping track of this damage is usually a difficult and expensive task because the mortality is typically scattered in erratic fashion over vast and often inaccessible areas. Often, excessively high costs can be avoided by using aerial photography, which covers ground more quickly and cheaply than fieldwork, yet provides a permanent in-place record of certain kinds of damage. This manual summarizes the present state of knowledge in this field and presents step-by-step procedures for the best known applications of aerial photography to forest insect surveys in the West.

The literature describes a wide variety of forest insect surveys, some of which can benefit from the use of aerial photos. From the standpoint of aerial photography, it is convenient to group these surveys into four classes, based on the type of information collected: (1) detecting the presence of damage, (2) determining the exact location of the damage, (3) estimating the amount of damage, and (4) estimating the relative size of the insect population and its capacity for future damage.

Aerial photography is not suited to initial damage detection or to the evaluation of insect populations. Early detection of insect damage requires rapid coverage of large areas on a regular schedule, a process best accomplished by visual aerial detection *(11)*. Information on the insect population and its potential for causing future damage can be obtained only by field examination. In many cases, the insects have left the tree by the time damage becomes visible from the air.

On the other hand, aerial photos can often contribute much towards obtaining estimates of mortality amounts and pinpointing the specific locations of the dead trees. A sampling procedure is generally used in estimating the total amount of dead or damaged timber. Some field checking is required, but aerial photos can be substituted for a large part of the fieldwork. Such a survey, based on combining information from both photo and field samples, will often cost less than a straight field survey of comparable accuracy.

Pinpointing the locations of dead or damaged trees requires a 100-percent survey rather than sampling. Here, again, aerial photos can often be used to reduce the amount of fieldwork required and lower the total survey cost.

In this manual, detailed methods are presented for using aerial photographs in these two principal types of surveys: (1) sampling to estimate amounts of damage or mortality and (2) complete coverage to locate the dead or damaged trees for salvage operations. Although several methods are available for combining photo and field samples, most studies and trial surveys have dealt with one—double sampling with regression. Consequently, this procedure will be covered in detail and the other sampling methods will be mentioned only briefly.

In addition to presenting the general procedures to be followed, there is a discussion of factors to be considered when one is deciding whether or not to use photos. Finally, there are some specific recommendations for the application of these survey methods to certain kinds of insect-caused damage, pointing out where these differ from the general methods described.

Although only two basic survey methods are presented, the information obtained from them is useful for many purposes. An estimate of the amount of current or accumulated mortality measures one source of drain on the forest resource and is used in adjusting the inventory and allowable cut calculations. Such estimates also comprise an important part of the information needed to make decisions on whether or not to control an insect outbreak, or whether or not to adjust logging plans for more emphasis on salvage.

Repeated estimates of damage amounts, annually or periodically, form an important historical record of damage trends. This record can be useful for determining when an outbreak has reached its peak and started to decline. Such damage trend information, when combined with data on the weather, stand conditions, and site factors, should furnish valuable clues to the reasons why outbreaks start, build up, continue, or drop off. When a project is undertaken to control an insect outbreak, a measure of the success or failure of the operation can be obtained by measuring the damage before and after control measures are taken, on both controlled and uncontrolled areas.

Pinpointing the location of dead and damaged trees is a vital preliminary step in planning salvage operations and is often useful in guiding the fieldwork during the actual operations. In certain situations, this information may also help in planning and executing control projects.

The methods described in this manual were developed over a period of years from a number of studies, tests, and trial surveys. Exploratory work in this field began in the 1920's in the pine stands of California and has been expanded since then, especially in the last 10 years. Aerial photographs have been successfully used in surveys of ponderosa pine mortality caused by the western pine beetle in southern Oregon (fig. 1), Douglas-fir mortality caused by the Douglas-fir beetle in western Oregon and Washington (fig. 2), and Pacific silver fir damage and mortality caused by the balsam woolly aphid in southwestern Washington (fig. 3A and 3B). They should also prove useful for certain other surveys, such as of mortality in immature ponderosa pine caused by the mountain pine beetle (fig. 3C).

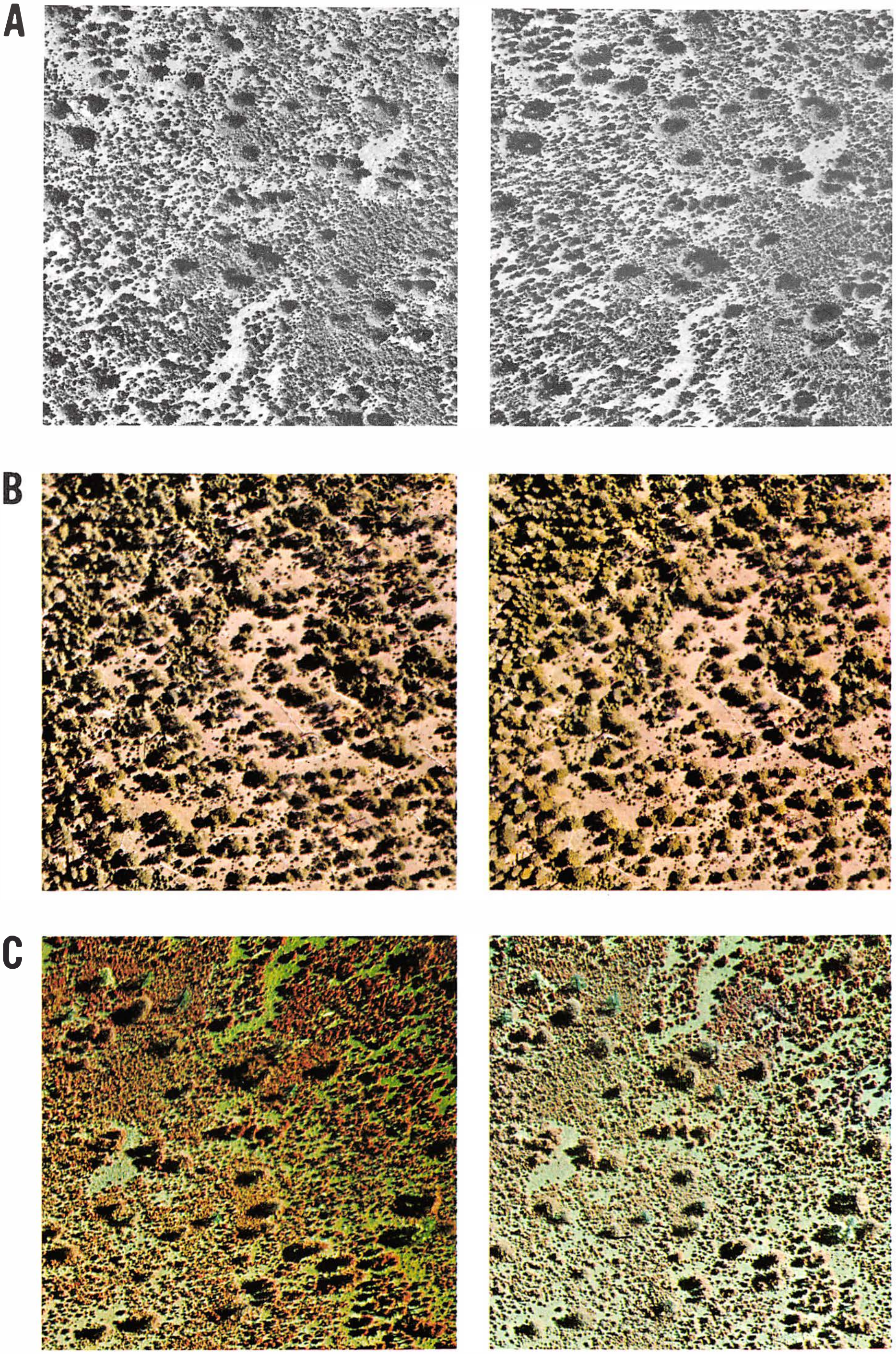


Figure 1.--Stereograms of

WESTERN PINE BEETLE DAMAGE. Scale 1:5,000

A. Panchromatic film (orange filter)

B. Color film

C. Ektachrome Infrared film

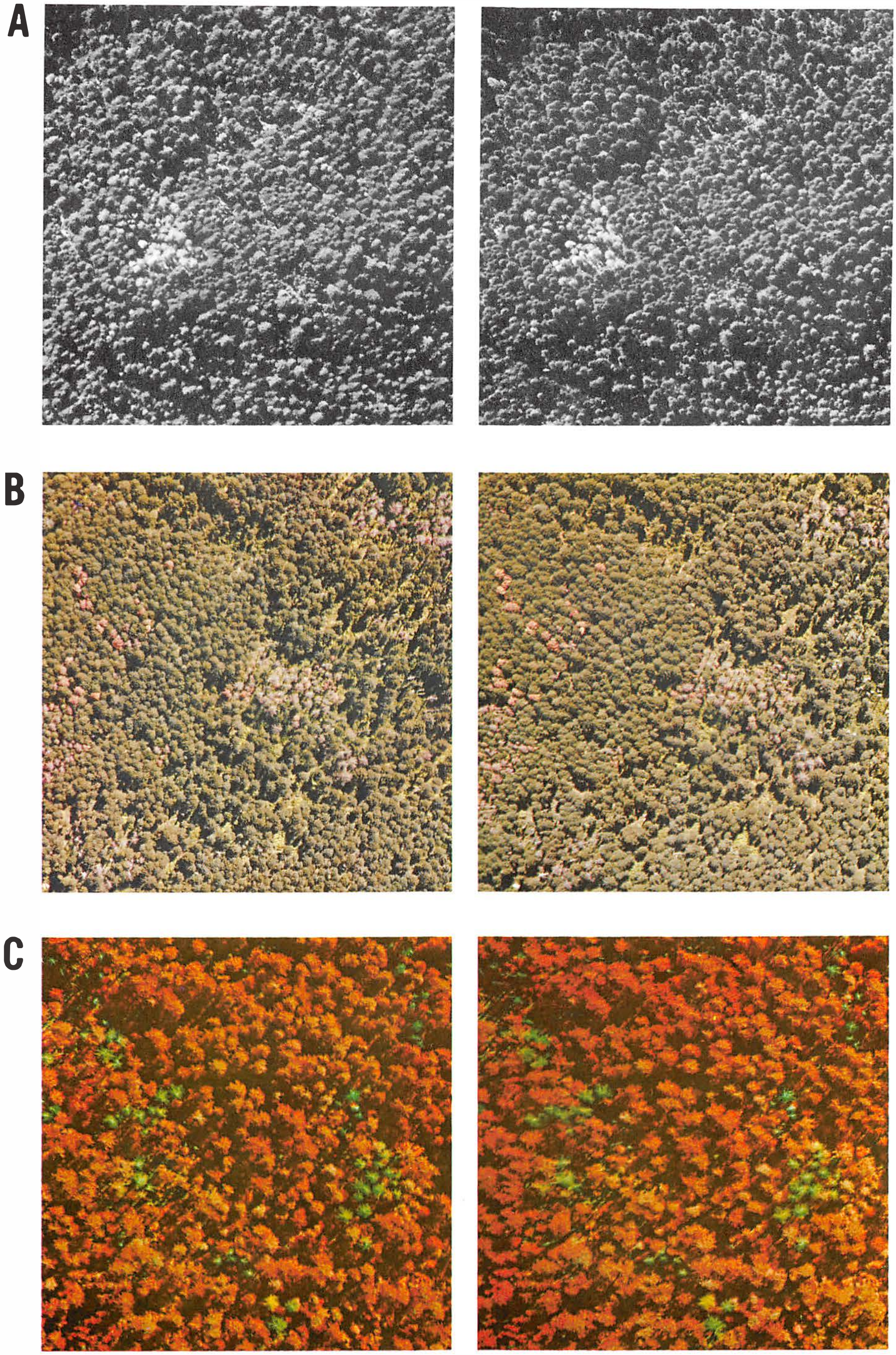


Figure 2.—Stereograms of

DOUGLAS-FIR BEETLE DAMAGE. Scale 1:7,920

A. Panchromatic film (red filter)

B. Color film

C. Ektachrome Infrared film

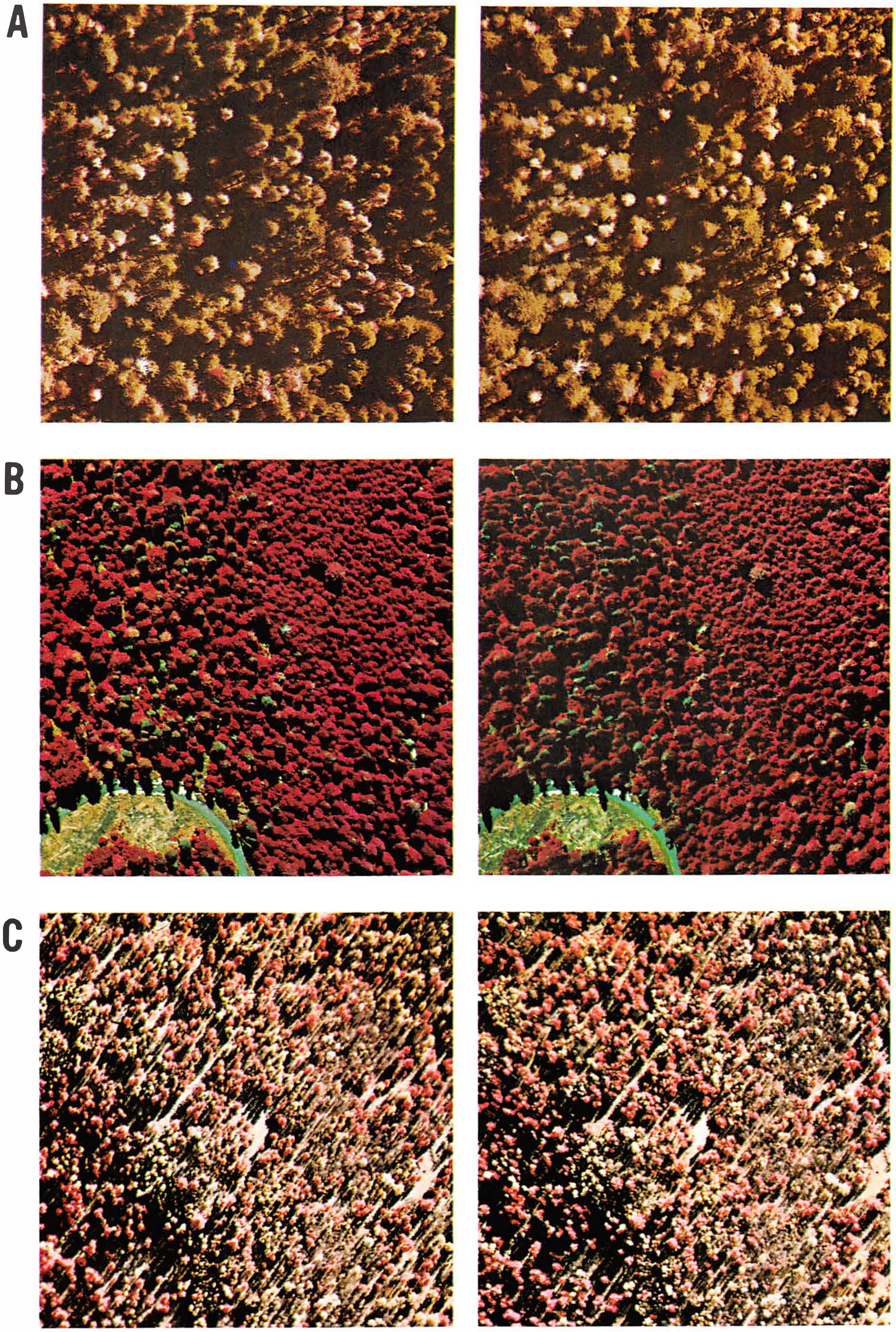


Figure 3.—Stereograms of
BALSAM WOOLLY APHID DAMAGE Scale 1:2,500
on Pacific silver fir.
A. Color film. B. Ektachrome Infrared film.
MOUNTAIN PINE BEETLE DAMAGE Scale 1:3,000
on immature ponderosa pine.
C. Ektachrome Infrared film

DOUBLE SAMPLING WITH REGRESSION

Double sampling with regression is one of the most efficient ways to combine information from both photo and field plots into an estimate of the amount of mortality or damage, such as by a forest insect outbreak *(3)*. The method employs two samples, or a sample within a sample. The first sample consists of a relatively large number of photo plots. On each plot the number of dead or damaged trees is counted, and their volume is calculated if desired. A portion of these plots is then visited in the field—the second sample—and the number or volume of dead or damaged trees on each is determined. The photo and field data for this second, or small, sample provide the basis for computing a linear regression expressing the relation between the photo and field measurements. The final estimate of the damage amount is obtained by using this regression to adjust the data from the first, or large, photo sample.

This method exploits the fact that photo measurements of damage or mortality tend to be related to the field measurements but are considerably cheaper. Under these conditions, the double sample with regression is likely to be more efficient than a simple sample of straight field plots, in the sense that it will provide better information at a given cost or equivalent information at lower cost. However, if the photo plots are not substantially cheaper than the field plots, or if the relation between photo and field measurements is poor, then it probably would not pay to use a double-sample survey with aerial photos.

Following is the prediction equation, or the formula for obtaining the adjusted estimate. The terminology follows that of Freese *(5)*.

$$\bar{y}_{Rd} = \bar{y}_2 + b(\bar{x}_1 - \bar{x}_2)$$

where:

$\bar{y}_{Rd}$ = estimate of average number or volume of dead or damaged trees from a regression double sample

$\bar{y}_2$ = mean of all field plot measurements in the second or small sample

b = regression coefficient of field on photo measurements from those plots that have both — the small sample

$\bar{x}_1$ = mean photo measurement of numbers or volume of dead or damaged trees from the large sample of photo plots

$\bar{x}_2$ = mean photo measurement of numbers or volume of dead or damaged trees from only those plots which were field checked — the small sample

A double-sample survey, then, is aimed at providing data to calculate the four items needed to solve the regression formula: mean photo measurement from the large sample, mean of both photo and field measurements from the small sample, ond the regression of field on photo measurements. How these dota are collected and how the calculations are made are described and illustrated in the step-by-step procedures which follow.

The method of double sampling with regression, as applied to a survey for estimating amounts of tree mortality or damage, generally consists of the following steps: (1) defining the area to be sampled, (2) determining size and shape of plots, (3) estimating numbers of plots needed, (4) establishing locations of plots, (5) obtaining aerial photos, (6) measuring the mortality or damage on the photos, (7) field checking a portion of the plots, and (8) calculating the estimate for the total amount of mortality or damage.

Discussion of an important preliminary step, that of deciding whether to use the double-sampling procedure with aerial photos or choose some alternative method such as a straight field survey, has been deferred until after the sampling method has been described and demonstrated. Some of the concepts are rather complex, and they will be easier to explain and to understand after the method itself has been covered. Moreover, decisions on whether or not to use double

sampling, and how many plots are needed, are best based on experience gained from previous surveys. Thus, the first survey of this type will be largely an experiment with choice of method and plot numbers based on available rules of thumb developed from other people's surveys. After some experience has been gained, these problems can be approached in the more sophisticated manner described later in the manual.

DEFINING THE AREA TO BE SAMPLED

A logical starting point for any survey is deciding exactly what area is to be sampled. This involves a two-phase procedure: delineating the boundary of the general area, and determining what specific areas within this boundary will actually be sampled.

Boundary delineation is best done by visual aerial reconnaissance from an airplane or helicopter. The limits of the area within which damage or mortality occurs can be sketched on a base map or, if the area is not too large, they can be marked on available aerial photo prints. Some spot checking on the ground is desirable to make sure that the damage seen from the air is of the type being surveyed; that is, the correct tree and insect species. Checks outside the boundary of visible damage are needed to determine if any substantial amounts of damage are being missed and to revise the boundary accordingly.

Under some conditions, it might be feasible to do no more than locate the boundary and let the plots fall anywhere within this. However, there is usually a substantial portion of the area within the gross survey boundary which should be eliminated from any chance of being sampled. This includes areas of nonforest or nonstocked land and timber stands of unaffected tree species or size classes. It is obviously inefficient to establish plot locations, take photographs, and send field crews out to inspect areas where no damage or mortality of the type being surveyed could possibly occur.

Thus it is important, if at all possible, to divide the area within the survey boundary into two classes: acres to be sampled and acres which should not be sampled. Information from type maps, cruises, available aerial photos, and visual aerial reconnaissance should be assembled to do the best possible job on this breakdown. Questionable areas should be included in the sample. This will probably result in visiting a few plots that do not have damage, but it is preferable to missing an unknown amount of damage in areas which should have been sampled.

The end result of this two-phase procedure for defining the area to be sampled will normally be a detailed map (fig. 4) which shows the boundary of the survey area and the specific areas to be sampled. It is used as the guide for locating sample plots and is the basis for determining the acreage of the areas to be sampled. This acreage becomes the factor for expanding the per-acre damage estimates from the plots to the total for the survey area.

SIZE AND SHAPE OF PLOTS

At present, little is known about the most efficient size and shape of plot for this type of survey. However, a few general guidelines can be given.

To begin with, the photo and field plots must be identical in size, shape, and location to assure a relation between the photo and field measurements of mortality or damage. This relationship can occur only when the interpreter and field crew are examining the same areas and looking at the same trees.

There is generally a conflict between what plot size and shape is most desirable from the standpoint of photo interpretation and that which is best for field checking. Once the photos have been taken and set up for interpretation, it doesn't cost much more to measure damage on a large plot than it does on a small one. From the photo

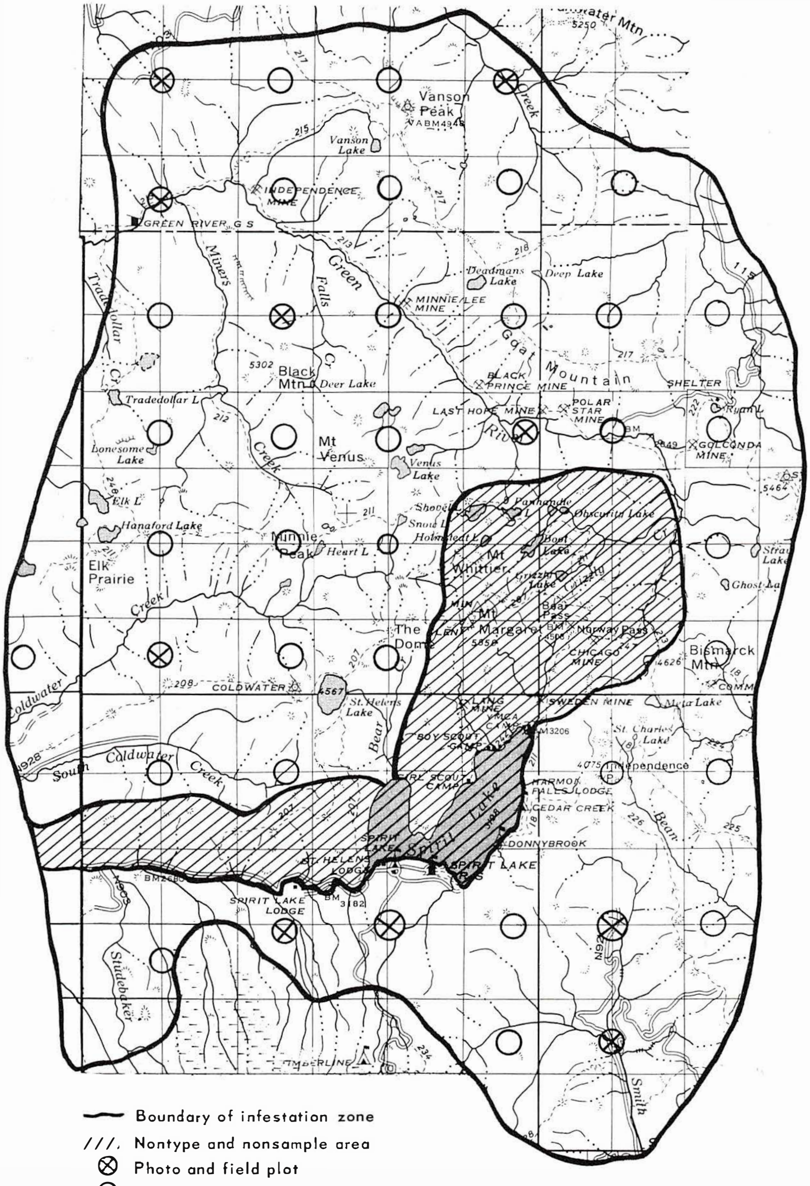


Figure 4.—Portion of double-sampling survey map.

standpoint, the larger the plot the better, and a rectangular one filling the overlap area is the largest that can be placed on a stereopair of photos.

Large plots also make it easier to determine the regression of field-plot-to-photo-plot values, which regression is used to adjust the large photo sample. When small plots are used, most will be found to have no mortality and the greatest amount on any plot is likely to be only two or three trees, making it difficult to establish a significant relation between the photo and field plot values: the range of mortality is too small and even occasional interpretation errors are serious when dealing with such small numbers. On the other hand, if the plot size is expanded so that the greatest amount of mortality is a dozen trees or more, the increased range and decreased seriousness of errors make it easier to get a significant relation between the photo and field plot values.

From the standpoint of field checking, however, there is a limit on the size of plot that can be reasonably handled. This is usually set at an average day's work for a crew. The final decision on plot size and shape, then, is likely to be a compromise. The plot should be as large as possible without exceeding a reasonable day's work for the field crew. In open stands, such as ponderosa pine, the plot should probably be square, or something near it, for orientation is usually easy in open stands. However, in dense stands it may be necessary to run a centerline and tally on a narrow strip to avoid getting lost.

Some plot sizes proving feasible in studies and operational surveys are: (1) 20 acres (10 by 20 chains) to 40 acres (20 by 20 chains) in ponderosa pine stands, (2) 8 acres (2 by 40 chains) in dense Douglas-fir stands, and (3) 1 acre (2 by 5 chains) in Pacific silver fir and hemlock stands.

ESTABLISHING LOCATIONS OF PLOTS

The next step normally would be to determine how many photo and field plots to establish in the areas to be sampled. However, as previously mentioned, this problem is being deferred until after the entire double-sampling procedure has been described. At this point, we assume that plot numbers have been determined, and the job now is to establish their locations.

Random selection or a systematic grid pattern may be used to locate the desired number of photo plots and determine which will be checked in the field. In either case, the map showing the survey boundary and actual areas to be sampled is the basis for choosing plot locations.

There is a variety of ways for locating the photo plots in random fashion. One of the easiest is to use random numbers to pick a township and then a section within it. The center of the section, or some other predetermined place within it, becomes the plot location. If this point falls on what the map shows is an area to be sampled, this becomes the location for a photo plot. If the point falls on an area that is not to be sampled, it is discarded. The process is repeated, gaining a plot location every time a point falls on an area to be sampled, until the required number of photo plot locations has been selected. There is a certain amount of lost motion in this process because some of the random points selected fall in nonsample areas and are rejected. If a randomly selected township has less than 36 sections, the draw to pick a random section within it should still be made by choosing from numbers 1 through 36. If the selected section does not exist in this township, no plot is established.

If many plots are to be selected, or if the area to be sampled is only a small portion of the gross area within the survey boundary, it is generally easier to establish a systematic grid of plot locations rather than choose them at random. Moreover, the bulk of the evidence

indicates that systematic sampling is likely to give a better estimate than random sampling. Its disadvantage is that sampling error calculations assume random sampling and are not strictly applicable to systematic samples.

To establish a systematic grid, the total acreage of the areas actually to be sampled is measured on the map. This acreage is divided by the desired number of photo plots to get the area represented by each plot. The spacing of the gridlines can then be chosen so that the squares or rectangles they bound contain this number of acres. For example, suppose the gross area within the survey boundary is a million acres, but the total acreage to be sampled is only about 750,000. If 100 photo plots are to be located, each will represent 7,500 acres. A few trial calculations show that a grid 3-½ miles square would encompass 7,840 acres, and one 3 miles by 4 miles contains 7,680 acres. Either grid design would be satisfactory.

A grid with the chosen interval is then constructed and laid in a random position over the map showing the areas to be sampled. Each grid intersection that falls on an area to be sampled becomes a photo plot location; the rest are rejected. In the above example, it is likely that about 130 grid intersections would fall within the survey boundary, but only about 100 of them would land on areas to be sampled.

Photo plot locations should be marked on the best large-scale maps or recent small-scale photos for the purpose of orienting the photo crew. The locations on existing aerial photo prints provide positive identification.

After the photo plots have been established, photographed, and interpreted, plots to be field checked are selected. The selection may be either random or systematic; it seems simplest to follow the same plan used in laying out the photo plots. For random selection, the photo plots can be numbered consecutively and random numbers used to choose the desired number of field plots. To select the field plots systematically, divide the number of photo plots by the number of field plots for the sampling fraction. Then choose a random number

between 1 and this number as a starting point. Take the remaining plots at intervals of the sampling fraction from then on. For example, to choose 20 field plots from 100 photo plots, start with a random number between 1 and 5, then select every fifth plot thereafter.

The chosen field plots should also be marked on maps or photos for field crew guidance. Existing photo prints of these locations help field crews find their way to plots. The job of marking plots on maps and existing photos should be done after the special photos have been taken. Only after these photos are available can the exact plot location be determined, because intended plot locations may have been missed.

OBTAINING AERIAL PHOTOS

In most cases, the aerial photos used in a forest insect survey will have to be taken especially for the particular survey. Accurate recognition and evaluation of dead or damaged trees usually require special films and larger-than-normal photo scales. Moreover, the photos commonly available would seldom have been taken at the right time for the survey.

Timing of Photography

Aerial photography should be scheduled during favorable weather and sun angle and generally at the season when damage from the most recent insect activity shows up best. If the photography is to be repeated to assess the annual trend of the damage, then the succeeding years' photos should be taken at the same stage of annual development as the first year's photos. To choose the best time for photography, it is necessary to have an understanding of the biology of the insect and the fading characteristics of the host tree and to consider what purpose the damage or mortality estimate is to serve.

For most bark beetles in the Pacific Northwest, the best time for photography is from mid-June to mid-July. At this time, most of the trees attacked the previous year have faded, but those trees attacked during the current year have not yet started to fade. In California, where some beetles have several generations a year, the fading pattern is more complex and photography requires more careful timing.

Timing of insect attacks and tree fading varies from year to year and place to place. It is therefore necessary to plan for a tentative photographic schedule at a time considered likely to be best, but to base the final decision on periodic checks made in the field or by aerial reconnaissance.

Scale of Photography

Studies have indicated that the larger the photo scale, the more accurate the detection and identification of insect-caused damage or mortality. Since the photo plots are generally distributed on a sample basis with two or three photos at each plot location, the total number of photos taken is about the same, regardless of photo scale. Therefore, large-scale photos cost no more than small-scale photos. Thus, there is some advantage in using the largest scale that can possibly be obtained.

There are, however, some disadvantages to extremely large photo scales taken with standard aerial cameras that do not have image motion compensation. For one thing, picture sharpness drops off because of the rapid image motion and the rough air usually encountered at low altitudes. Adequate overlap between photos also becomes difficult to maintain with the cycling times available in many cameras. Moreover, the ground area covered by large-scale photos is so limited that field crews are likely to have difficulty finding their way to the plots.

Thus, the scale for sample aerial photos to be used in a survey of insect-caused damage or mortality is generally a compromise. A scale of 1:4,000 to 1:5,000 appears to be about the best compromise known at present. Tree mortality and severe damage to upper crowns show up well at such a scale, yet image quality remains satisfactory, and sufficient ground is covered by a 9- by 9-inch photo that the field crews have a reasonable chance of finding the plots. When the damage is of a type that is more difficult to distinguish, such as that caused by defoliators or weevils, larger scales are likely to be required *(2)*. This may call for special camera equipment and create contracting problems. Advice should be sought from someone experienced in this kind of photography.

Photographic Films

Of the four types of film generally available, three have proven useful in surveys of insect-caused damage or mortality. These are panchromatic, color, and Ektachrome Infrared (a special color film formerly called camouflage-detection). The other film, regular infrared, has not been satisfactory. It records dead conifers in much the same dark tone as live ones, making it virtually impossible to separate the two classes.

In general, it is more difficult to separate dead from live trees on panchromatic prints than it is with one of the color films. On the other hand, panchromatic film is cheaper, the prints are familiar to most foresters, and they are easier to use stereoscopically in the field than are color transparencies.

On panchromatic film, the dead trees tend to photograph much lighter than the live ones. If the dead trees have yellow, orange, or red foliage, an orange filter used with the panchromatic film emphasizes the tone difference and makes it easier to distinguish between live and dead trees. This distinction is easiest when the mortality is in large groups such as those caused by heavy epidemics of the Douglas-fir beetle; it is much more difficult when the dead trees are scattered singly or in small groups, typical of light infestations of the western pine beetle.

The detection and identification of tree damage and mortality are usually more reliable on one of the color films. The standard color films, such as Anscochrome, Ektachrome, and Ektacolor, show objects in their natural colors. It is much easier to separate the yellows, reds, and browns of dead foliage from the greens of live foliage on these films than it is to distinguish them as shades of gray on panchromatic prints.

Ektachrome Infrared film combines infrared and color emulsions. Healthy green foliage shows in various tones of pink and red, fading foliage appears yellow or chartreuse, and dead foliage is dark green. Due to this striking color contrast, dead and dying trees can be spotted more quickly than on any other type of film, though accuracy of interpretation is about the same as on the standard types of color film. These unusual color effects may make Ektachrome Infrared film less desirable than regular color films when it is to be used for a variety of purposes in addition to damage or mortality evaluation.

Photographs produced from color films come in two forms. Anscochrome, Ektachrome, and Ektachrome Infrared films become positive transparencies which must be viewed by transmitted light. They are thus less convenient to interpret stereoscopically than photographic prints, though navigating in the field with single transparencies has been successful. Ektacolor film is transformed into a negative transparency with colors that are complementary to the actual colors of the objects photographed. From this negative it is possible to make color transparencies, color prints, or black-and-white prints.

This feature of Ektacolor, besides making it versatile, has several other advantages. Color prints are more convenient to interpret than transparencies. Moreover, in the process of making a color print, it is possible to exert some control over the general color balance and density. On the other hand, color prints, besides being very expensive, don't seem to have quite the sharpness or color saturation of transparencies.

Because color film is more expensive than panchromatic and there is a greater risk in storing, exposing, and processing it, color photography costs more. Just how much more is difficult to predict. The cost of

obtaining color transparencies has been reported to exceed that of panchromatic by amounts ranging from 10 or 20 percent to 50 or 60 percent. The cost of color prints runs substantially higher.

This variation is probably due to two causes: (1) most studies have been made by people who took their own photos and therefore weren't able to determine the commercial cost, and (2) many aerial contractors haven't had much experience with color photography and their prices haven't settled down. As more and more color photography is used, not only for insect surveys but also for other purposes, its cost fluctuations should become smaller, eventually settling down at perhaps 20 or 30 percent more than panchromatic. Meanwhile, the only way to be sure of what color photography will cost is to get an estimate from a contractor.

In spite of the higher cost, color transparencies are usually a better value than panchromatic film because of the speedier interpretation and greater accuracy. This may not be true of color prints because of their considerably greater expense. Our experience indicates that color photos should be a better value than panchromatic if they don't cost more than about twice as much.

Contracting Considerations

Help on setting up photography contract specifications can be obtained from several publications *(1, 2)*, and personal contact with foresters who have prepared specifications is advisable whenever possible. Some highway photography is flown at large scales, and reviewing contracts of this type should be especially helpful. However, the specialized types of photography generally required for forest insect surveys are relatively new to both foresters and contractors.

Where photo scales larger than 1:10,000 are being used and the camera format is 9 by 9 inches, a lens of at least 12-inch focal length should be specified. Moreover, the overlap between photos should be 70 or 80 percent, rather than the standard 60 percent. If

both of these cautions are not met, the photos are likely to exhibit too much parallax, or vertical exaggeration, making stereo viewing difficult.

Another problem of large-scale photos is the difficulty of determining photo scale. The scale of each group of photos must be determined so that the proper size of plot can be laid out. With normal-scale photos, the scale is usually determined by measuring distances between pairs of checkpoints which can be identified both on the photos and a map. However, large-scale photos cover such a small ground area that it is seldom possible to pick out two checkpoints that show on a map.

If normal-scale photos are available, their scale can usually be obtained from a map, then used to get the scale of the special insect survey photos. If normal-scale photos are not available, it will be necessary to make special provisions when contracting for the insect survey photos so that their scale can be determined. One way to do this is to determine the elevation of each plot from topographic maps, then require the contractor to fly a constant height above these, using his barometric altimeter. Another way is to require the contractor to use a radio or radar altimeter and record the flying height at each plot.

Taking large-scale color photos of sample plots is a specialized job. The photo points are often in heavily forested areas where good landmarks are scarce and map detail is limited. Close coordination between pilot and photographer is essential, and team experience in this type of photography is highly desirable. The forester contracting for large-scale sample plot photography should try to obtain an operator with an experienced photo team.

Photos of good quality and adequate coverage are essential for forest insect surveys made by the double-sampling method. These qualities are difficult to spell out in detail, and the project forester or his representative will have to pass judgment on the photos received from the contractor.

Pictures should be sharp and clear. Panchromatic prints should have a good range of tones and are best if slightly softer or flatter than the average type of print used in forest inventory or management — more on the order of prints preferred by cartographers (fig. 2). Glossy prints seem to yield a little more detail than semimatte and are therefore best for interpretation, though not for field checking. Standard color photos should have an overall color balance that appears normal to the eye, and Ektachrome Infrared photos should have a good range of reds and greens (fig. 3).

It cannot be expected that all sample plot photographs will fall exactly where they have been pinpointed on maps or existing small-scale photos. In any group of randomly or systematically chosen locations, some will be far enough from visible landmarks that it is impossible to photograph their exact location. As long as such photos fall in the vicinity of the right location, they are not likely to be biased and can be used in the survey.

PHOTO INTERPRETATION

The interpreter's job is to search the photographs, detect and identify damage or mortality of the particular type being inventoried, and record this in terms of numbers of trees over a certain minimum size or in terms of timber volume. He is a key figure in the success of the double-sampling method, and to do a good job he must have adequate training, use suitable equipment, and follow proper methods.

Training

As a minimum, an interpreter on a forest insect survey should be experienced in forest photo interpretation. That is, he should be able to quickly orient the photos for proper viewing, be able to see the stereo image without difficulty, and be familiar with the characteristics that help distinguish one tree species from another. Additional experience specifically on forest insect damage recognition is desirable.

Regardless of the interpreter's experience, he will need a certain amount of training on the particular survey, working with the type of photography being used and with the specific damage or mortality being inventoried. To meet this need, special provisions should be made in the survey plans and scheduling. Ideally, the first job of the field crews would be to annotate on the photos, but not on the actual plots, a series of trees representing not only the various stages of damage being inventoried, but also other things that might be confused with them. The interpreter can then study the sample trees, make his decisions, and check his answers with the field data. Additional knowledge can be gained if he makes a short trip into the field to determine the causes of his errors.

Laying Out Plots

Before the interpretation can begin, plot boundaries must be laid out on the photos. The contractor has attempted to take each stereo pair or triplet at specific plot locations indicated on maps or existing aerial photographs. As the interpreter checks the new photos for proper location, he will undoubtedly find varying degrees of accuracy. Some of the intended plot locations will fall near the center of the new photo coverage, some may fall near the edge, and others may be clear off the photos or at some indeterminate location.

A logical solution to this is to shift the plot location to the center of the photos, since it is likely to be an unbiased location. If a stereo pair is used, the plot can be placed midway between the two photo centers; if a triplet is used, it can be placed at the center of the middle photo.

The plot center can be marked on the photos, and then, when the plot is interpreted, a transparent overlay showing the plot boundary can be used. Or, alternatively, the plot boundary can be marked on the photos. In either case, the scale of the photos at each plot must be determined, by one of the methods previously discussed, so that the plot boundary can be made the right size.

Interpretation Methods

The interpretation consists of orienting the photos properly for stereoscopic viewing, and systematically searching the plot for trees to be inventoried. Trees of the specified species and size that have been damaged or killed during a particular period, usually the last 12 months, are annotated or counted.

Photo orientation is standard, as for any stereoscopic viewing, with the principal and conjugate principal points in line and the photos spaced for the particular stereoscope being used. Panchromatic or color prints may be interpreted with either a pocket stereoscope or a mirror type. Color transparencies must be viewed on a light-table. If a pocket stereoscope is to be used, the table must have a slot in the center through which the inside edges of the photos are tucked *(9)*; this is not necessary with a mirror stereoscope. An excellent setup for interpreting transparencies consists of an Old Delft scanning stereoscope with variable magnification and a light-table with a series of controllable lights (fig. 5). With such a light-table, it is possible to balance illumination between transparencies of uneven density or to reduce illumination for overexposed transparencies.

Figure 5.—Office photo interpretation, using mirror stereoscope and light-table.

To minimize the chance of missing some of the dead or damaged trees, the interpreter should follow a systematic method of searching the plot area. A grid that divides the plot into squares or rectangles should be placed over the plot and each square searched carefully before moving on to the next. Within a square, each tree should be scrutinized and recorded if it is dead or damaged.

Close attention should be paid to tree shadows in open stands. Occasionally, such a shadow will reveal the presence of a tree whose crown is difficult to distinguish and would probably otherwise be missed. Shadows also sometimes indicate that what appears to be one crown is really two or more trees and may enable the interpreter to spot a dead or damaged tree that is partly overtopped. The density of the crown shadow is useful in judging the date of tree death; crowns with full foliage cast dense shadows, and those with only partial foliage cast thinner shadows.

When apparently dead trees are encountered, they should be examined carefully in an effort to determine if they are completely dead or only topkilled. It is not always possible to make this distinction, but diligent scrutiny may reveal some green foliage at the bottom of the crown. This often shows up best where the tree is near the photo edge, since this oblique view shows more of the crown side. When three or more photos have been taken at a plot location, it will pay to examine a suspicious tree on every photo.

Although the appearance of dead or damaged trees varies somewhat, there is a fairly consistent pattern for each film type:

1. PANCHROMATIC PRINTS. Healthy green conifer crowns are dark toned. Dying foliage that has turned yellow, orange, or red is light toned (fig. 2), especially when the photos have been taken with an orange or red filter. Tree crowns with all dead foliage still present are smooth and full. Partial foliage makes the tree crown look thin, rough, and darker gray in tone. When foliage and small twigs fall, trees have a light-toned, skeletonized appearance.

2. COLOR TRANSPARENCIES AND PRINTS. Color transparencies and prints show tree conditions in their actual colors — green when undamaged, then yellow, orange, red, and brown as foliage fades. After the needles have dropped, crowns are purplish. Tree crowns look gray and thin after the small twigs fall. The typical snaglike appearance is the final stage after small branches have dropped (fig. 1, 2).

3. EKTACHROME INFRARED TRANSPARENCIES. The expected colors are reversed on Ektachrome Infrared film. Live green foliage appears in shades of red, depending upon the size and type of tree — dark red for old trees to light pink for seedlings and saplings. Damaged tree crowns are first a dull, dark red; as the foliage dies, crowns show yellow green; and when the foliage falls, crowns appear green to dark green. Dead snags have a pale-green, skeletonized appearance (fig. 1).

The interpreter's tally of dead or damaged trees can be in terms of tree numbers or estimated volume, whichever is desired for the final survey estimate. If both types of data are desired, it is probably best to estimate both on the photos, rather than make only a tree count and later apply an average volume per tree.

The results of surveys conducted so far indicate that estimates of the total volume of dead or damaged trees are likely to have less sampling error than estimates of total tree numbers. The reason seems to be that the trees most often missed are in the intermediate or suppressed crown classes, with volumes well below average. When tree counts are being made, it is just as serious to miss a small tree as it is a large one. However, when the objective is to estimate the total volume loss on a plot, missing a small, low-volume tree does not seriously affect the result.

The volume in a dead or damaged tree can be determined by measuring or estimating its total height and crown diameter, then applying one of the available aerial-photo tree-volume tables. A satisfactory shortcut, however, is merely classifying each tree into one of several broad size classes, such as large, medium, and small. These can be rather arbitrary and based on crown diameter alone or on both height

and crown diameter. Later, an average volume can be assumed for each size class in order to estimate the total volume on each plot. It is not necessary that the photo volumes agree with the field volumes for the same plots. The field check is used to adjust the photo volumes, and it is important only that there be a reasonably consistent relation between the two.

FIELDWORK

The job of the field crews is to visit selected plots and determine the number or volume of dead or damaged trees. As a minimum, this involves locating the plot by means of aerial photos, establishing the plot boundary, and recording the dead or damaged trees. If it is desired to analyze the interpretation errors in an effort to improve future accuracy, the field crews should be required to record additional data that will aid in this analysis.

The time of the fieldwork should coincide with photography. The photography probably has been taken at a time when most of the trees attacked the previous year have faded, but those attacked during the current year have not yet started to fade. This is also the time when the year of attack is easiest to distinguish in the field. If the fieldwork is done much before this time, some of the trees attacked the previous year but not yet faded will be missed. If fieldwork is delayed much beyond the date of photography, new fades from the current year's attacks may be recorded as previous year's mortality.

Training

The field plot tally is the basis for adjusting the photo measurements, so it is essential that the work be done as accurately as possible. Field personnel should be experienced in using aerial photos to find their way around in the woods and in identifying insect-

killed or damaged trees. Field crews should be given whatever additional training is necessary to insure that they are proficient in the two major field tasks: (1) keeping track of where they are, both on the ground ond on aerial photos, and (2) identifying the particular type of insect-caused damage or mortality being surveyed, including the year of attack, and separating it from the other kinds of damage with which it might be confused.

Methods

LOCATING PLOTS ON THE GROUND.—The field crew's first job is to locate the plot which has been marked on the photos. The usual procedure is to drive as close as possible to the plot, using maps and normal-scale photo prints for guidance. The normal-scale photos are then used to navigate across country to the vicinity of the plot, working from one landmark to the next, or occasionally running a compass and pace line in a direction and distance measured on the photos. Once in the vicinity of the plot, the large-scale photos are used to identify the plot boundary.

CRUISING TECHNIQUES.—The type of field data collected and the methods of collecting it vary somewhat with the survey objectives and the manner in which the data will be used. There are three considerations which influence the methods of conducting the fieldwork. These are: (1) whether the plots are temporary or permanent, (2) whether the severity of the current year's attacks is to be evaluated as an indicator of trend, and (3) whether the reasons for interpretation errors are to be analyzed.

If the survey is aimed not only at estimating the current loss but also at establishing a base for measuring the trend of future damage, then the trees which are tallied must be marked. The dead trees should be blazed or tagged and labeled with the date of death. Only in this manner can crews who remeasure the plot distinguish trees

that died since plot establishment from those that died before. If additional documentation is desired, the dead trees can also be marked on the aerial photos and be given an identifying number or date of death.

If the purpose of the survey is to estimate only the current loss, then marking the tallied trees is not required as a base for future remeasurements. However, marking is still desirable to enable the supervisor to check on the accuracy of the fieldwork and to point out to field crews why they are making mistakes.

When the only estimate desired is that of the damage caused by the previous year's bark beetle attacks, field crews can usually confine their attention to trees with faded foliage. The survey will generally be conducted at a time when trees attacked the previous year have faded, whereas those attacked the current year will still be green. Having identified the trees to be tallied, field crews should record as a minimum: species, d.b.h, and height, or whatever else is necessary to determine volume.

If it is also desired to estimate the loss from the current year's attacks, all trees within the plot will have to be carefully inspected. These trees will normally have green foliage and the only evidence of bark beetle attacks will be pitch tubes and frass in bark crevices. In addition to species and whatever measurements are required to calculate volume, crews will have to record the identity of currently infested trees separately from the others.

A survey that includes an analysis of interpretation errors requires the greatest field effort. Each dead or dying tree is spotted on the photos by the photo cruiser and is analyzed by the spotters. The additional data to be tallied should include:

1. Topkills or progressive kills with dead foliage

2. Previous year's mortality

3. Mortality older than 1 year with dead foliage

4. Dead trees of other species

5. Needle complement; i.e., full, moderate, or sparse

6. Needle color; i.e., green, straw, orange, rust

7. Other trees or objects that might be confused with tree mortality.

Cruising plots on the ground with aerial photographs is a different procedure than for standard ground surveys. An efficient size for ponderosa pine plots is 20 acres, 10 by 20 chains. An average three-man photo survey crew can usually locate and cruise two widely separated plots per day. The crew member with photo experience, the photo cruiser (PC), maintains plot orientation along a 1-chain strip on the outside edge of the plot while the two spotters (S) check trees in the 4-chain strip adjacent to the PC (fig. 6). Each insect-killed tree is blazed and dated by the spotters. The survey objectives determine how much of the above data is to be recorded on plot cards by the PC.

The photo cruiser uses stereo and nonstereo interpretation procedures for maintaining orientation in the field. With the development of a portable split light-table (fig. 7), stereo interpretation of color transparencies is quite simple *(9)*. This small, lightweight, battery-powered light-table can also be used conveniently in the office on 110 volts a.c.

Frequently, it is not necessary to have a stereoscopic model for viewing color transparencies. A single transparency can be held up to the light of the sky (fig. 8) or be illuminated by reflected light from a bright surface such as a tatum holder. Trees and ground detail are adequately depicted to establish most ground positions and tree locations. In dense stands or steep topography having considerable shadows, stereo interpretation is generally needed for good orientation.

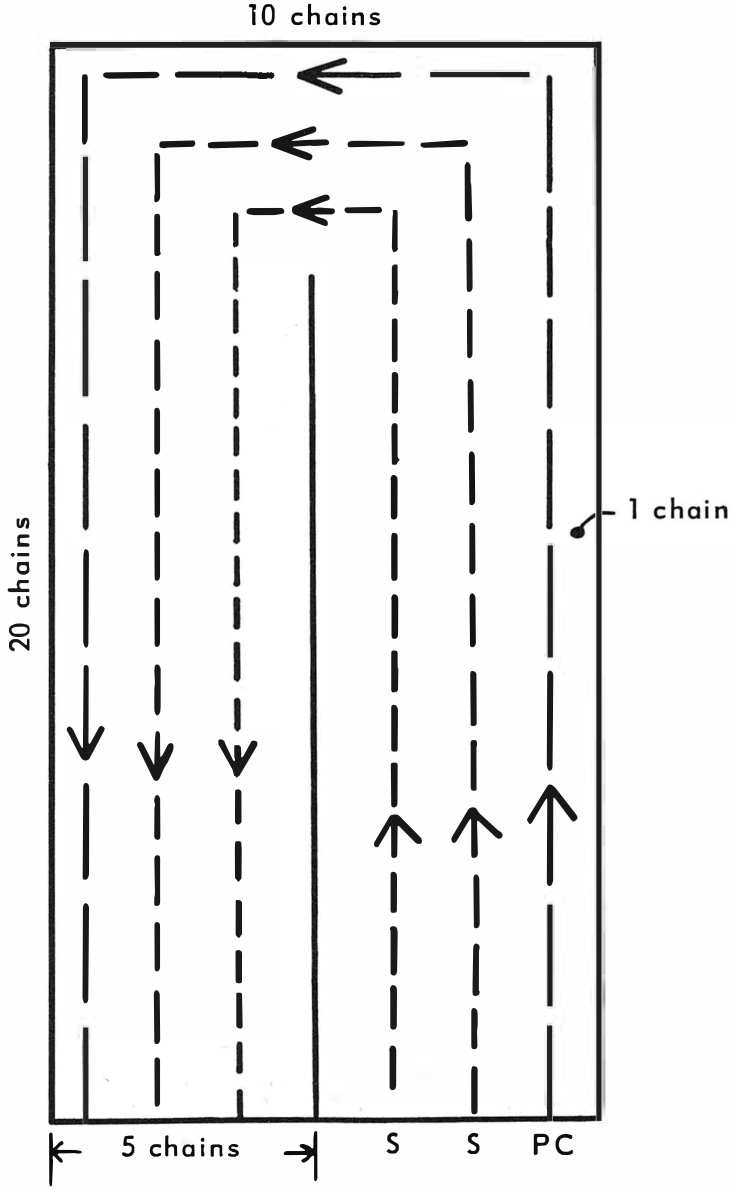
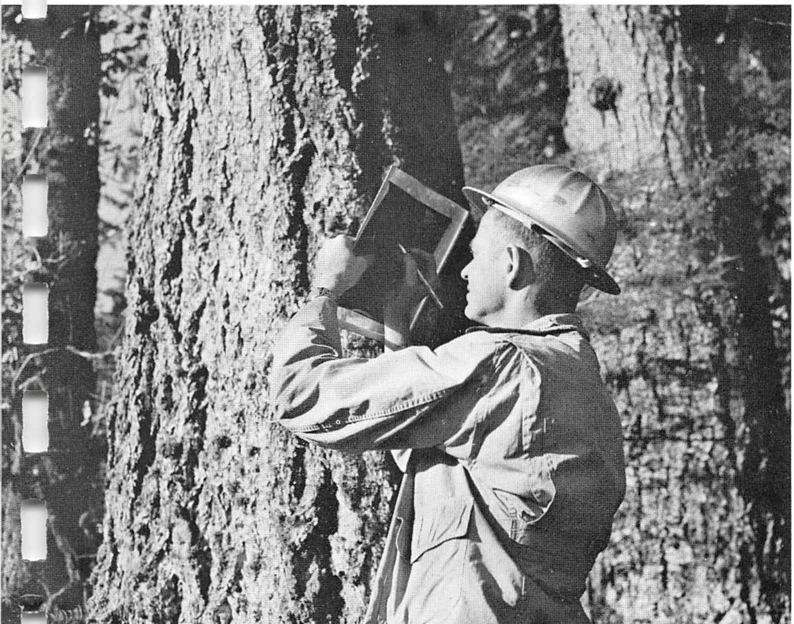


Figure 6.—Typical ground plot for photo cruising in ponderosa pine.

Figure 7.—Portable light-table for viewing color transparencies in the field.

Figure 8.—Single color transparency used to pinpoint tree locations and orient crew in the field.



The different plot sizes for various timber types have been mentioned. The cruising techniques vary only slightly for different strip widths. On long, narrow plots, 1, 2, or 5 chains wide, the photo cruiser maintains orientation along the centerline of the strip. The number of spotters varies from two for the 2- and 5-chain strips to only one for the 1-chain strip. Data collected are based on survey objectives.

CHECKING FIELDWORK. — Usually the field supervisor and an entomologist will make the ground check of the crew's work. Two or three plots from the first six taken should be inspected to make sure they are in the correct location and the desired type of damage is being correctly identified. Weaknesses in training can be detected at this time and corrected. Any discrepancies, such as errors of omission, incorrect dating or identification, should be noted by the inspectors. These plots should be recruised with the original field crew to correct mistakes and emphasize the need for accurate fieldwork.

Periodic field checks are made during the course of fieldwork to insure high work standards and maintain crew morale. If initial field checks for a crew are satisfactory, only two or three plots need to be checked as a followup. If frequent mistakes are made by a crew, heavier checking is required throughout.

COMPUTATIONS

The final step in the double-sample survey is to calculate the total number or volume of dead or damaged trees from the combined photo and field data, then determine the reliability of this estimate by computing its sampling error. These procedures will be illustrated by an example, using data from a trial survey of pine mortality in the Blacks Mountain area of northern California. The objective is to estimate the total number of dead pine trees. As before, the terminology follows that of Freese *(5)*.

Estimate of Mortality

Assume that 100 photo plots have been established, each 20 acres in size, and that an interpreter has counted the number of pine trees believed to have died in the past year on each plot. This is called the large photo sample. The total number of dead trees on all plots is 452 and the average is 4.52 trees per plot. In formula form:

$$\bar{x}_1 = \Sigma x_1/n_1 = 452/100 = 4.52 \text{ trees per plot}$$

where:

- $\bar{x}_1$ = mean count of large photo sample
- x_1 = interpreter's count of dead trees on a plot in the large photo sample
- n_1 = number of plots in the large photo sample
- Σ = symbol meaning to "sum all values of."

Twenty of the 100 photo plots have been visited in the field, and a count has been made of the actual number of pine trees that have died in the past year. The following tabulation shows both the photo and field tree counts for these 20 plots, called the small sample:

	Photo count (x_2)	Field count (y_2)
	12	9
	2	1
	0	0
	1	0
	2	1
	24	15
	0	0
	0	1
	2	2
	6	2
	1	1
	1	0
	5	3
	0	0
	8	1
	12	10
	1	0
	0	0
	3	7
	3	3
	—	—
TOTAL	83	56

From these data, five sets of calculations must be made to compute the estimated number of dead trees per plot from the combined photo and field data:

(1) The mean photo count on the small sample.

$\bar{x}_2 = \Sigma x_2/n_2 = 83/20 = 4.15$ trees per plot

where:

x_2 = interpreter's count on a photo plot which has been subsampled in the field.

n_2 = number of plots in the field subsample, or small sample.

(2) The mean field count on the small sample.

$\bar{y}_2 = \Sigma y_2/n_2 = 56/20 = 2.80$ trees per plot

where:

y_2 = field count of dead trees on a field plot.

(3) The sum-squares of x.

$$SS_x = \Sigma x^2 - \frac{(\Sigma x)^2}{n_2} = (12^2 + 2^2 \ldots + 3^2) - \frac{(83)^2}{20} = 678.6.$$

(4) The summed cross products of x and y.

$$SP_{xy} = \Sigma xy - \frac{(\Sigma x)(\Sigma y)}{n_2} = (12)(9) + (2)(1) \ldots + (3)(3)$$

$$- \frac{(83)(56)}{20} = 429.6.$$

(5) The regression coefficient of y on x.

$$b = \frac{SP_{xy}}{SS_x} = \frac{429.6}{678.6} = 0.633$$

This is all that is needed to compute the estimated number of dead trees per plot from the combined photo and field plot data (the adjusted mean from the regression double sample).

$$\bar{y}_{Rd} = \bar{y}_2 + b(\bar{x}_1 - \bar{x}_2) = 2.80 + (0.633)(4.52 - 4.15)$$
$$= 3.03 \text{ trees per plot.}$$

Figure 9 shows in graphic form just how this last equation combines the photo and field data from the two samples. The photo and field

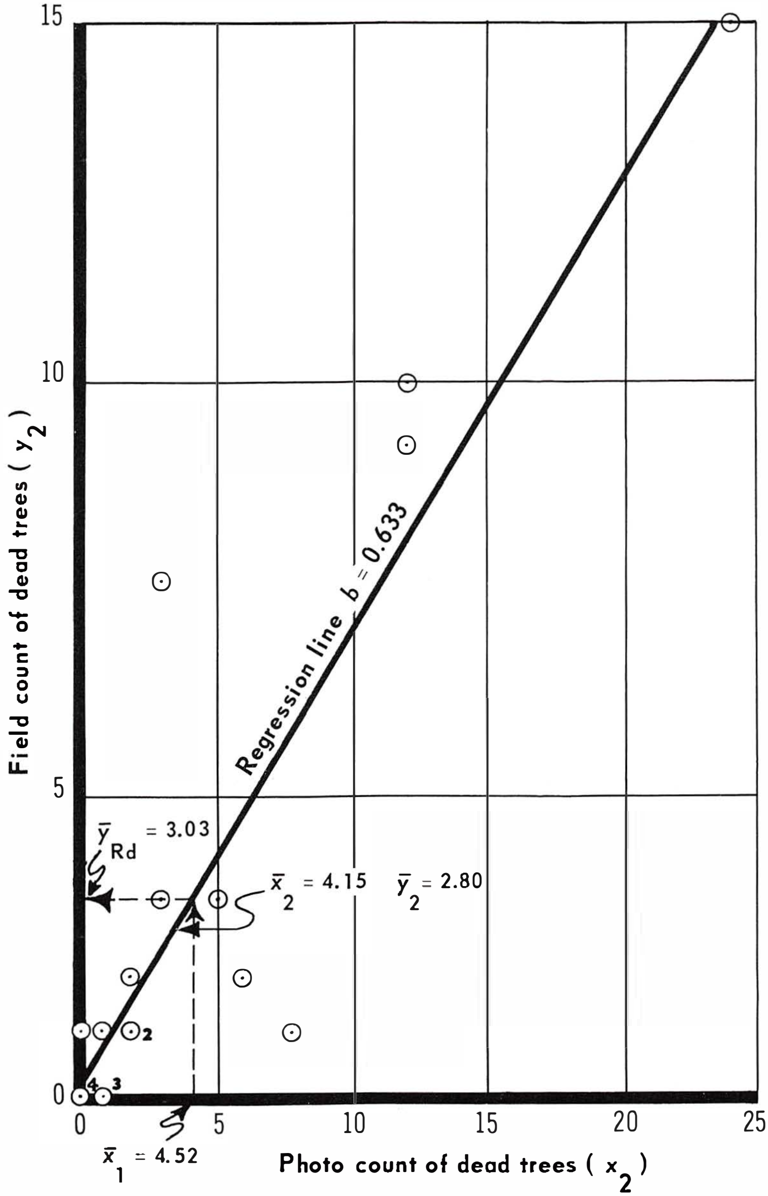


Figure 9.—Linear regression of field count of dead trees over photo count of dead trees for 20 plots.

counts for each of the 20 plots in the small sample have been plotted, with the field estimate (y_2) on the vertical axis and the photo estimate (x_2) on the horizontal axis. A linear regression line has been fitted through these 20 points. It goes through the mean of the field estimates $(\bar{y}_2)$ and the mean of the photo estimates from the small sample $(\bar{x}_2)$ and its slope is that of the regression coefficient (b); that is, for each unit of x, the line rises 0.633 units of y. Now, to get the estimated number of dead trees from the regression double sample, the x-axis is entered at the value of the mean from the large photo sample $(\bar{x}_1)$ A line is followed vertically until it strikes the regression line, then horizontally until it strikes the y-axis. At this point, the answer $(\bar{y}_{Rd})$ can be read.

To estimate the total number of trees on the surveyed area, we divide the plot average by the plot size to get trees per acre and multiply by the number of acres in the surveyed area. Thus, if the foregoing survey, using 20-acre plots, covered 125,000 acres, the estimated total number of trees killed in the last year is:

$$\hat{Y} = \frac{3.03}{20}(125{,}000) = 18{,}938$$

Sampling Error Determination

It is possible to end the calculations after getting the estimate of the total mortality from the combination of field and photo plots. However, it is difficult to know how much reliability to place in this estimate unless the sampling error is computed. Such a computation is well worth the small amount of extra time it takes.

To calculate the sampling error, it is necessary to go back to the original photo and field data for the 20 plots in the small sample and compute the following additional items:

(6) The sum-squares of y.

$$SS_y = \Sigma y^2 - \frac{(\Sigma y)^2}{n_2} = (9^2 + 1^2 \ldots + 3^2) - \frac{(56)^2}{20} = 329.2.$$

(7) The variance of y.

$$S_y^2 = \frac{SS_y}{n_2-1} = \frac{329.2}{20\text{-}1} = 17.33.$$

Now, by use of these items, plus some of those previously calculated, the sampling error is computed in two steps.

First, the variance from regression is computed.

$$S_{y \cdot x}^2 = \frac{SS_y - \frac{(SP_{xy})^2}{SS_x}}{n_2 - 2} = \frac{329.2 - \frac{(429.6)^2}{678.6}}{20 - 2} = 3.178.$$

Next, the sampling error itself is calculated.

$$S_{\bar{y}_{Rd}} = \sqrt{S_{y \cdot x}^2\left(\frac{1}{n_2} + \frac{(\bar{x}_1 - \bar{x}_2)^2}{SS_x}\right)\left(1 - \frac{n_2}{n_1}\right) + \frac{S_y^2}{n_1}}$$

$$= \sqrt{3.178\left(\frac{1}{20} + \frac{(4.52 - 4.15)^2}{678.6}\right)\left(1 - \frac{20}{100}\right) + \frac{17.33}{100}}$$

$$= 0.548 \text{ trees per plot.}$$

This is the standard error for the estimated average number of trees per plot ($\bar{y}_{Rd} = 3.03$). Thus, the estimate could be written:

$$\bar{y}_{Rd} = 3.03 \pm 0.55 \text{ trees per plot.}$$

In percent, the standard error is 0.548/3.03 = 0.181, or 18.1 percent. The estimated total number of dead trees (18,938) has a standard error of (0.181) (18,938) = 3,428, and the estimate with its confidence limits (at one standard error) can be written:

$$\hat{Y} = 18,938 \pm 3,428.$$

Like all sampling error calculations, the foregoing procedure is based on the assumption that random sampling has been used; methods for estimating sampling errors from systematic samples are not presently known. However, the most commonly accepted method for systematic samples is to go ahead and calculate sampling error using the random

sampling formulas, then regard this as probably the maximum sampling error. That is, it is usually assumed that the actual sampling error is no more than the calculated error and is probably less.

WHEN TO USE THE PHOTOGRAPHIC METHOD

Discussion of a very important point has been delayed until this time. This is the question of when to use one of the photographic sampling methods and when an alternative technique, such as the straight field survey, should be chosen. It has been necessary to first detail the method of double sampling with regression so that the reader can follow the discussion on how to weigh the advantages and disadvantages of possible survey methods.

A logical basis for choosing between alternative methods is to pick the one which seems likely to produce the most for the money. This means the one which will give the lowest sampling error for a given cost or, to put it another way, will produce a given sampling error at least cost. The method which does this is said to be the most "efficient" one.

There may be circumstances that clearly dictate the survey method to be used, regardless of which is most efficient. Examples of situations that preclude using aerial photography are: season when photos can't be taken, insufficient time to contract for photography, or no experienced interpreter available. On the other hand, a scarcity of trained field personnel might cause a forester to choose the photographic approach, even though it is less efficient than a field survey, because it requires less fieldwork.

Usually, however, either method is feasible, and deciding between them is a matter of trying to judge which will deliver the most information per dollar of cost. This section explains how to predict the efficiency of a double-sample survey relative to a straight field survey and discusses the factors that affect this efficiency.

PREDICTING EFFICIENCY

The following explanation of how to predict whether the photographic approach will be more or less efficient than a straight field survey is limited to the previously described method of double sampling with regression. However, the same general approach can be used with other methods of combining photo and field data.

In attempting to predict which will be more efficient — a straight field survey or one employing aerial photos in a system of double sampling with regression — it is first necessary to estimate two things. These are the cost ratio of a field plot to a photo plot and the coefficient of correlation between the photo- and field-plot data.

Plot Costs

The cost of both photo and field plots varies from area to area and from time to time because of different conditions, making it difficult to give any rules of thumb for plot costs.

Most land managers will have had enough experience with field plots to make a reasonable estimate of field-plot cost. As a rule, the plot size is chosen to fit into an average workday for a crew. Thus, on an extensive survey in the dense forests and rough topography of the Douglas-fir subregion, a crew of two or three men will probably average only one plot a day, and the plot size will have to be restricted to a few acres to accomplish this. On the other hand, in open pine stands on gentle topography, a crew may be able to average two or three 10- to 40-acre plots a day.

With plot size geared to a crew's average workday, it is relatively easy to estimate field-plot cost from the known salary and travel expenses. In surveys which have been conducted in the Pacific Northwest, 5- to 10-acre plots in Douglas-fir and true fir stands have cost from $75 to $100 each. In ponderosa pine stands, 20- to 40-acre plots have run from $25 to $50 each.

Although the cost of a photo plot should not be influenced by plot size or photo scale, it is affected by some less tangible factors, such as profit margin, and is therefore more difficult to predict than field-plot costs. The only sure way of getting an estimate is to talk to a reputable photo contractor. However, as a rough guide, past experience suggests that 100 photo plots systematically scattered over about 500,000 acres should cost around $12 to $15 each.

Correlation Coefficient

The second estimate needed for predicting whether a double-sample survey will be more or less efficient than a straight field survey is the coefficient of correlation between photo- and field-plot mortality data. This is a measure of the linear association between the two sets of data. If there is no linear association at all, then the correlation coefficient will tend to be zero. However, if there is a strong linear association between photo and field mortality counts; e.g., if plots with large photo counts of mortality tend to have large field tallies and plots with small photo counts of mortality tend to have little or no field tally, then the correlation coefficient will approach its maximum value of +1.0. It is possible for a correlation coefficient to be negative, but this is not likely with this type of data.

Figure 9 shows one example of linear association between tree mortality counts made on photos and in the field on a series of 20 plots. The photo and field counts for each plot are shown as a scatter diagram. Note that there is a strong tendency for plots that have a low photo count to also have a low field count, and plots with a high photo count tend to have a high field count. The association appears to be linear; at least, there is no indication of a curve, and a straight line seems to express the relationship as well as any other line that could be drawn. The correlation coefficient for this particular data is 0.91. If all points had fallen on a straight line, it would have been 1.0.

Even though the correlation coefficient to be expected on a particular survey varies with a good many factors which are discussed later, it seems desirable to provide at least some rough guide for use by those who are contemplating their first double-sample survey. Past experience indicates that, with good quality aerial color photography, an interpreter with some experience in this field should be able to get about the following results when estimating mortality volumes or numbers of trees killed by bark beetle epidemics:

Timber type	Plot size	Correlation coefficient
Ponderosa pine	20 acres	0.8
Douglas-fir	5 to 10 acres	0.9

There is some evidence from limited studies that estimates of mortality or severe damage caused by other kinds of insects in other timber types should yield similar results as long as the damage is visible from the air.

Calculation Procedure

Having estimated the plot-cost ratio and the expected correlation coefficient, it is now possible to predict the efficiency of a double-sample survey relative to a straight field survey. Simply refer to the graph in figure 10, locate the appropriate cost ratio and correlation coefficient, and read off the corresponding efficiency. For example, if field plots cost \$90 and photo plots cost \$15 (plot-cost ratio = 6) and the expected correlation coefficient is 0.90, the predicted efficiency would be about 1.6. This means that the double-sample survey can be expected to produce an estimate of mortality with a precision equal to that of a straight field survey costing 1.6 times as much.

Several assumptions, which are an unavoidable part of the calculations that produced this graph, tend to make it slightly optimistic

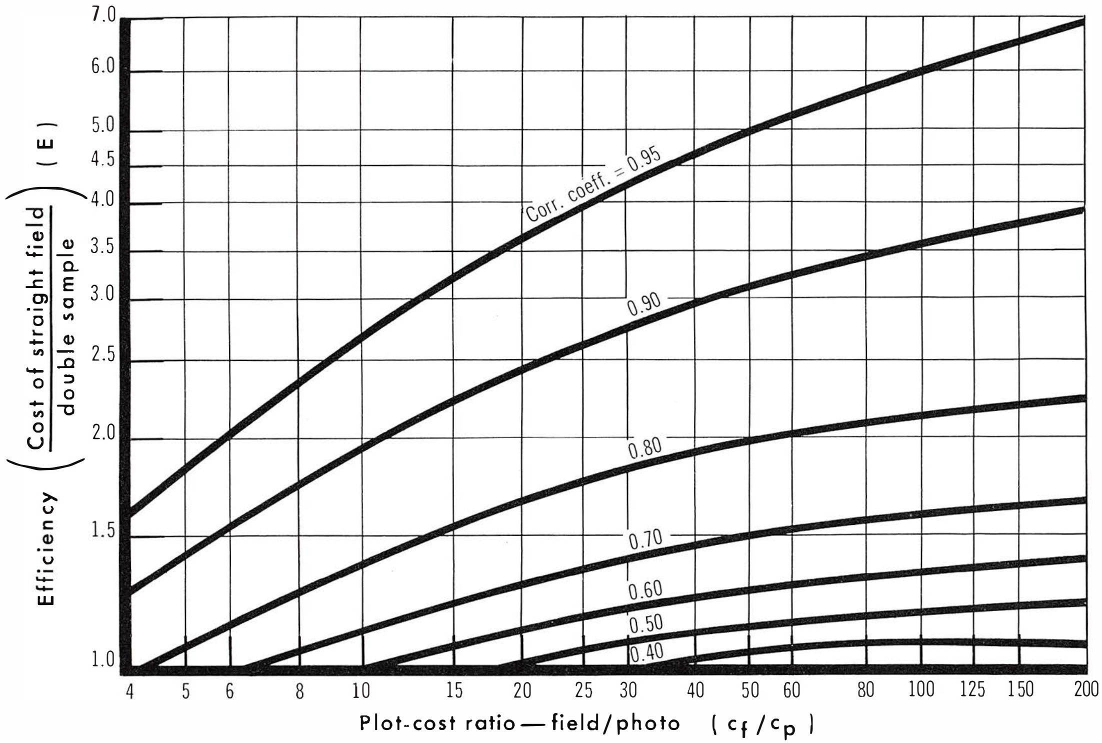


Figure 10.—Efficiency of double sampling with regression.

in favor of the double-sample survey. It would, therefore, be well not to adopt the double-sample survey unless its expected efficiency is somewhat higher than 1.0, say about 1.2. Thus, with a plot-cost ratio of 6 and an expected correlation coefficient of 0.80, the indicated efficiency is only about 1.2. Under these conditions, the two types of surveys should be considered about a tossup in terms of information produced per dollar of cost.

FACTORS AFFECTING EFFICIENCY

It has been pointed out that, unless special circumstances dictate the particular survey method, the logical choice is the one that is the most efficient. When a double-sample survey is compared with a straight field survey, this efficiency is dependent on the relative cost of field and photo plots and on the expected coefficient of correlation between photo and field plot mortality estimates. There are a number of factors that affect either the cost ratio or the correlation coefficient and, thus, the relative efficiency of the two types of surveys. The effect of these factors on survey efficiency may vary from year to year and from one infestation to another. It is therefore desirable to examine each of them before undertaking a survey and to attempt to ferret out any conditions which might cause either the plot-cost ratio or the correlation coefficient to drop to the point where a double-sample survey would be less efficient than a straight field survey. The major factors affecting plot-cost ratio have already been discussed. Other factors that should be considered, primarily because of their influence on the correlation coefficient, are: ease of damage recognition, experience of photo interpreter, and obstacles to good photography.

Ease of Damage Recognition

The most obvious limitation of the photographic survey method is whether or not insect damage or mortality can be readily distinguished on aerial photos. The major influencing factors are the nature of the damage itself and the amount of additional damage from other sources which might be confused with the particular damage being inventoried.

CHARACTER OF DAMAGE. — Damage or mortality caused by insects must be distinct to be recorded on the photographs. This means the damage should be apparent in the upper crown; it should be in trees that are not overtopped; and the entire upper crown surface, or a substantial portion of it, must be a distinctly different color than that of healthy foliage. Results from several studies *(10,12,13)* also indicate that it is easier to estimate amounts of damage or mortality when the general level of loss is high, as in an epidemic. When only an occasional tree is killed or damaged, the inevitable interpretation errors are likely to be a substantial portion of the actual damage.

Before a decision is made to use aerial photos in sampling for damage or mortality estimates, the nature of the damage should be examined. If it occurs mainly in understory trees or in the lower portion of the crowns, if it does not cause a distinct change in foliage color, or if the damage intensity is at a low or endemic level, the photographic approach should not be used.

DAMAGE FROM OTHER SOURCES. — It is usually not possible to identify the cause of tree mortality or damage from its appearance on aerial photos. Moreover, it is often difficult to estimate the species of dead trees. Hence, it is usually impossible to identify current damage or mortality caused by a particular insect if there is intermingled damage of other tree species, damage from other causes, or if there is an accumulation of several years' mortality *(14)*. The survey area should be scouted for the presence of such damage; i.e., topkilling, or mortality caused by other insects, fire, weather, or any agent other than the one for which the survey is being conducted. If much of

this extraneous damage is present, interpretation accuracy is likely to suffer, and a survey based on aerial photography is not likely to be satisfactory.

Experience of Photo Interpreter

The interpreter must have experience in basic aerial photo interpretation techniques, a forestry background in differentiating timber types, and an understanding of the forest insect survey problem. Generally, he can be trained in the office and field on the appearance of damage by a specific forest insect that is being evaluated.

Obstacles to Good Photography

Local conditions of weather, terrain, and sun angle can affect the cost or quality of aerial photos and may even prevent photos from being taken at the time when the damage shows up best. Although such factors are mainly the concern of the photographic contractor, the forester should weigh their possible adverse effect on the photo project. Some of these factors may constitute a serious threat to the success of the photographic approach.

WEATHER. — The scheduling of photography for a damage evaluation survey is usually timed to catch the damage when it shows up best for a particular period of insect activity. This may or may not be the best time from the standpoint of weather. The chief problem is clouds. Persistent cloud cover delays photo projects, increases the cost, and may preclude photography entirely. Scattered clouds over any photo points delay photography and increase travel time and photo costs. As a guide for planning a photo survey in a particular region, weather records should be checked for the average number of cloudless days during the specific period needed for survey. In addition, local weather conditions for a specific survey area should be checked for daily cloud buildup.

Smoke or haze from forest fires or slash burning often becomes dense, obscures visibility, and thus prevents aerial photography, especially in valleys or basins where it tends to concentrate. In western Oregon and Washington, it is unwise to plan photography after the fall slash-burning season starts.

Another condition that occasionally hinders aerial photography is air turbulence. At the low flying heights required for large-scale photos, the air sometimes gets rough enough to impair photo quality or actually prevent photography. In warm parts of the country, during summer months, turbulence caused by thermal air currents may eliminate photography during the midday hours, the time of best sun angle. In mountainous country, turbulence can be caused by air currents over the rough terrain. Use of a longer lens, permitting higher flights for a given photo scale, may help minimize the problem of air turbulence.

TERRAIN CHARACTERISTICS. — Extremes in topography affect the planning of photo survey projects. Large-scale photography in high, mountainous terrain or steep canyons creates a twofold problem. Changes in elevation in short distances may be so great that the scale of aerial photography will vary. Dangerous conditions may also be encountered at low elevations due to downdrafts and turbulence. When such conditions exist on the survey area, either the scale of photography must be decreased to permit safe operations at a higher altitude or an aerial camera with a longer focal length lens must be used to secure the desired photo scale.

The average elevation or datum in high, mountainous terrain may require special aircraft and oxygen equipment. A datum of 7,500 feet will require an airplane with a service ceiling of about 18,000 feet to obtain a photo scale of 1:7,920 in an efficient manner. Because of higher operating costs, aerial photography in this situation will cost more than photography at a datum of 2,500 feet.

SUN ANGLE. -— High sun angle and minimum shadow result in maximum illumination of tree crowns, thus facilitating interpretation of insect-caused damage as recorded on aerial photos. In the United States, the sun never gets directly overhead, but the southern portions of the

country have a longer season of high sun angle than do the northern parts. In late June at latitude 45° N., photography for insect surveys should be taken between 10 a.m. and 2 p.m. sun time. Earlier and later in the year, relatively less time is available. From October to April, sun angle is low for insect-survey photography and resultant photos are seldom of the quality needed for accurate interpretation. North-facing slopes in steep terrain are illuminated for shorter periods than other slopes, a factor that must be taken into account on areas dominated by north slopes.

ESTIMATING SAMPLE SIZE

In describing the procedure of double sampling with regression, we pointed out that, after defining the area to be sampled and establishing the size and shape of plots to be used, the third step normally consists of estimating the numbers of plots needed. These numbers may be governed by the establishment of a desired sampling error, by financial limitations, or, as is more often the case, by a compromise between the two.

It is not easy to predict the exact numbers of plots needed to meet a desired sampling error nor to predict what sampling error will result from spending a certain amount of money. Nevertheless, an effort to approximate them is usually worth while. It will generally insure that you neither wind up with a sampling error so large the estimate is useless nor waste effort on obtaining a precision that is beyond your needs. In this section we will describe, and illustrate by example, how to estimate the numbers of photo and field plots required to meet a desired sampling error, and then show how to modify this when it is desired to set a limit on the total cost.

Both approaches require that you estimate three parameters: the field-plot/photo-plot cost ratio, the coefficient of correlation between photo- and field-plot mortality, and the coefficient of variation for field-plot mortality. The first two of these have already been covered in the section on "When to Use the Photographic Method."

The coefficient of variation for field-plot mortality is a measure of how variable the mortality is from plot to plot. It depends primarily on the nature of the mortality itself and the size of the plots. Insect-caused mortality tends to be one of the most variable elements of the forest, making for much higher coefficients of variation than, for example, does total inventory volume. Large plots tend to produce lower coefficients of variation than do small plots, since there is more

chance to capture at least some mortality on each plot, and the heavy patches are likely to be diluted by areas of no mortality.

As with plot-cost ratio and correlation coefficient, the best guide to estimating the coefficient of variation is experience data from previous surveys. However, foresters making their first mortality survey will have to rely on some other source of experience. Surveys that have been made in the Pacific Northwest show that coefficients of variation typically run around 125 percent or 150 percent for several types of epidemic mortality. These include ponderosa pine mortality caused by the western pine beetle, as measured on 10- to 20-acre plots; Douglas-fir mortality caused by the Douglas-fir beetle, as measured on 5- to 10-acre plots; and Pacific silver fir mortality caused by the balsam woolly aphid, as measured on 1- to 5-acre plots.

SAMPLE SIZE BASED ON DESIRED SAMPLING ERROR

If sample size is to be governed by the desired sampling error, you must, of course, decide at what level to set this error. This is something each will have to figure out for himself — there are no rules of thumb or recommendations we can make. One logical approach is to weigh the consequences of coming up with an estimate that may be in error by various magnitudes. In this manner, it is often possible to arrive at an approximate sampling error that is in keeping with the purpose of the survey.

Keep in mind that the desired sampling error, as we will use it here, is the standard error expressed as a percentage and represents a range on either side of the estimated mortality, within which the estimate from a 100-percent field survey should fall, unless a one-in-three chance has occurred. There always exists that one-in-three chance that the estimate from the 100-percent field survey might fall outside the confidence limits set by the estimate plus or minus its standard error.

Notice that the foregoing discussion did not use the term "*true* mortality," substituting in its place the estimate from a 100-percent field survey. This is because sampling error takes account of sampling variation only. It cannot account for such things as bias in the sampling method, errors in field measurement, or mistakes in computation. These sources of error cannot be evaluated, and must be held to a minimum by proper sampling design, adequate training, and careful supervision.

Calculations

The numbers of both photo and field plots required to meet a specified sampling error can be estimated by following the steps listed below.

1. Establish the desired or allowable sampling error *(AE)* and estimate the photo plot cost (c_p), field plot cost (c_f), coefficient of variation for field plots *(CV)*, and coefficient of correlation between photo and field plots (r).

Example: AE = 5 percent; c_p = \$10; c_f = \$50;

CV = 125 percent; r = 0.90

2. Use the graph in figure 10 to determine the efficiency of a double-sample survey relative to a straight field survey.

Example: With a plot-cost ratio of 50/10 = 5 and with a correlation coefficient (r) = 0.90, the indicated efficiency is about 1.4. (E = 1.4.)

It was pointed out earlier that as the efficiency of the double-sample method approaches 1.0, the cost of this procedure for a given sampling error approaches that of a straight field survey. Actually, the break-even point is probably around 1.1 or 1.2. Therefore, if the expected efficiency of a double-sample survey is only 1.1 or 1.2, you are not

likely to save any money by this method. If the efficiency is higher than this, or if you decide to try the double-sample method anyhow, proceed with the next step.

3. Determine the optimum ratio of photo plots to field plots from the graph in figure 11.

Example: With a plot-cost ratio of 5 and a correlation coefficient of 0.90, the optimum plot ratio is about 4.6. ($R = 4.6$.)

4. Calculate the required number of field plots, using the following formula:

$$n_f = \left(\frac{CV}{AE}\right)^2 \frac{c_f}{(E)[c_f + (R)(c_p)]}$$

Example: $n_f = \left(\frac{125}{5}\right)^2 \frac{50}{1.4\ [50 + (4.6)\ (10)]}$

$n_f = (625)\ (0.372) = 232.5$, or 233.

5. Determine the required number of photo plots, using the following formula:

$$n_p = n_f(R)$$

Example: $n_p = 232.5(4.6) = 1{,}070$

The calculations in the foregoing example indicate that to estimate total mortality with a standard error of 5 percent should require about 233 field plots and 1,070 photo plots. Total plot costs for the double-sample survey (C_d) would be: (233)($50) + (1,070)($10) = $22,350.

It is interesting to calculate what the cost would be for a straight field survey. The number of field plots required for such a survey is:

$n_f = \left(\frac{CV}{AE}\right)^2 = 625$. The total cost would be: (625)($50) = $31,250.

This is 1.4 times the cost of the double-sample survey, a figure that agrees with the efficiency as determined in step 2.

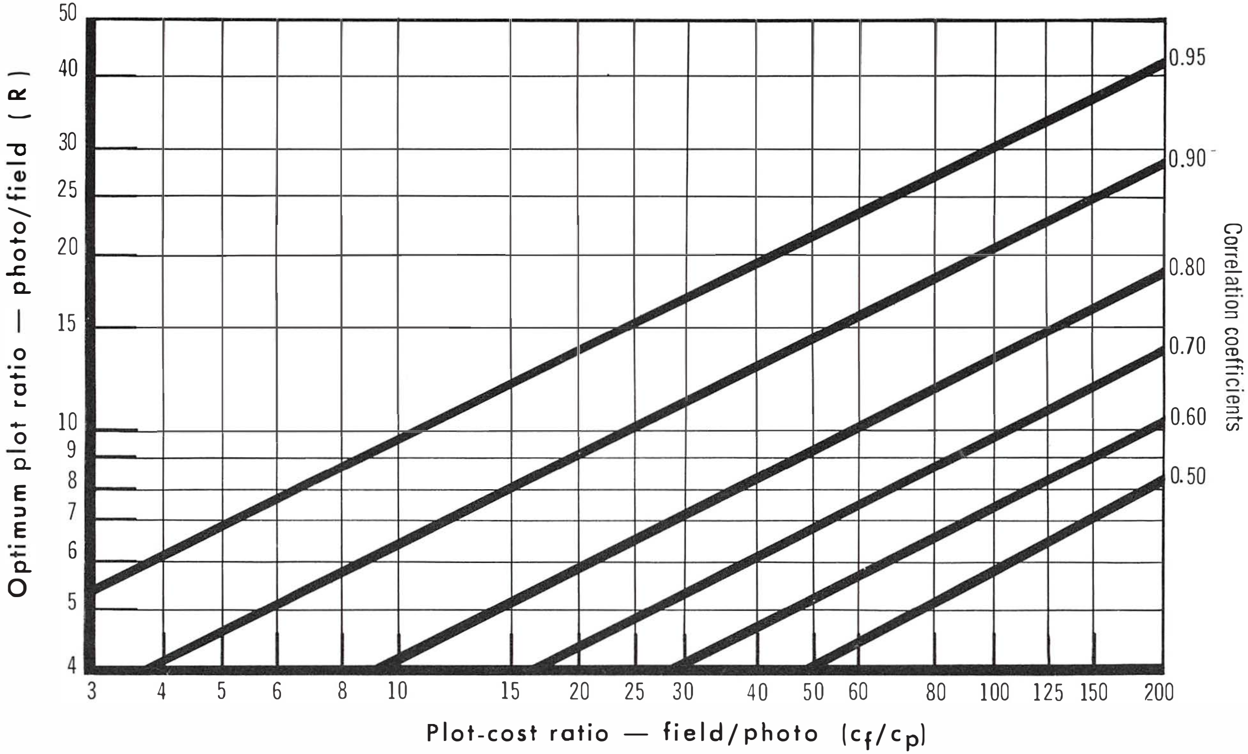


Figure 11.—Optimum ratio of photo plots to field plots.

MODIFYING SAMPLE SIZE TO MEET LIMITED FINANCES

There is a good chance that the land manager in the foregoing example would decide that he couldn't afford $22,350 for a mortality estimate. After reconsidering, he might feel that he could manage with a standard error larger than 5 percent and reduce the cost of the survey.

Suppose he decides that he can afford to spend $12,000 on the survey ($C_d$ = 12,000), and now he wants to know what standard error to expect and how many photo and field plots to take. The original estimates for coefficient of variation (CV = 125 percent), field-plot cost (c_f = $50), photo-plot cost ($c_p$ = $10), and correlation coefficient (r = 0.90) remain the same. Furthermore, simply changing the total survey expenditure doesn't change the previously determined efficiency (E = 1.4) or the optimum plot ratio (R = 4.6). With these data, the expected standard error and the required numbers of field and photo plots can be calculated as follows:

1. Compute the expected standard error in percent, using the following formula:

$$SE \text{ (percent)} = \frac{CV}{\sqrt{(C_d/c_f)E}} = \frac{125}{\sqrt{(12{,}000/50)\,(1.4)}}$$
$$= 6.82 \text{ percent}$$

2. Calculate the required number of field plots, using the following formula:

$$n_f = \frac{C_d}{c_f + (R)\,(c_p)} = \frac{12{,}000}{50 + (4.6)\,(10)} = 125$$

3. Calculate the required number of photo plots, using the following formula:

$$n_p = (R)n_f = (4.6)\,(125) = 575$$

As a double check, the total plot cost for the double-sample survey can be calculated by:

$$C_d = (n_f)(c_f) + (n_p)(c_p) = (125)(\$50) + (575)(\$10) = \$12{,}000.$$

The foregoing calculations indicate that by reducing the total plot costs from $22,321 to $12,000, and taking only 575 photo plots and 125 field plots, the expected standard error is increased from 5.0 percent to 6.82 percent.

OTHER PHOTO SAMPLING METHODS

Most surveys of insect-caused mortality that have been conducted in the Pacific Northwest have employed the method of double sampling with regression. Consequently, this is the procedure that has been presented in detail. However, there are several other sampling designs which could be used for this type of survey. Since little experience has been gained with these methods, they will not be described in detail but merely outlined briefly.

SIMPLE SAMPLING WITH PHOTO PLOTS ALONE

It is possible to obtain a rough estimate of the amount of damage or mortality from the photos alone. Photographs are taken of a series of plots distributed over an area of known insect activity. Plot boundaries are laid out on the photos, and the number of trees judged to be dead or damaged is counted on each plot. If volume, rather than tree numbers, is desired, tree size can be measured on the photos and converted to volume by use of an aerial photo volume table.

If an interpreter has made a number of such surveys, which later proved to be fairly reliable, some confidence can be placed in this method. However, without any field checking, there is always a risk that conditions in the current survey may be somewhat different from those in past surveys and create an unknown amount of error. This approach should probably be reserved for those occasions when some sort of estimate is needed, yet inaccessibility or lack of manpower prevents any field checking. Visual aerial reconnaissance techniques should also be considered under these conditions. They are quicker and cheaper but do not provide the detailed permanent record desirable for the measurement of trends.

STRATIFIED SAMPLING WITH PHOTO PLOTS

If previous visual aerial reconnaissance has produced a map showing the infestation area divided into damage intensity classes, this map could be used to stratify a series of aerial photo plots. This may produce a better estimate than simple sampling with photo plots alone, but the same unknown element of risk is present.

DOUBLE SAMPLING FOR STRATIFICATION

Under this variation of double sampling, the photo plots are placed in categories or strata according to number of dead trees counted. For example, one stratum might contain all photo plots with zero counts, another might contain all plots on which either one or two dead trees were counted, and a third might contain all plots with three or more dead trees. Finally, a portion of the photo plots in each stratum would be selected for ground examination. The estimated total number of dead trees can then be found with this formula:

$$\hat{Y} = \frac{A}{n} \Sigma(n_i \bar{y}_i)$$

where:

$\hat{Y}$ = estimated total number of dead trees on entire survey unit

A = gross area of survey unit in acres

n = total number of photo plots over all strata

n_i = number of photo plots in the ith stratum

$\bar{y}_i$ = average number of dead trees per acre in the ith stratum from the ground sample.

Double sampling for stratification may sometimes be less efficient than double sampling with regression, in the sense that the estimate of total dead trees may have somewhat more sampling error for a given survey cost. However, most people find it easier to understand, and it might be preferred for that reason.

RATIO DOUBLE SAMPLING

If field counts of dead trees are plotted over corresponding photo counts on graph paper, the scatter of points may tend to focus on the zero-zero coordinates of the graph, and the scatter of the points may also tend to increase as the photo count increases. These two characteristics of the data, if present, would suggest a possible theoretical advantage for ratio double sampling over regression double sampling. There has apparently been no attempt to exploit this possible advantage so far, but it needs to be explored further.

SURVEYS TO MEASURE MORTALITY TRENDS

At times, it is desirable to keep track of the trend in damage or mortality that occurs over a period of years. A record of the annual mortality caused by an insect epidemic can be useful in studying the dynamics of such outbreaks. This type of survey can also be used to evaluate the effectiveness of an insect control project.

The most practical way to follow mortality or damage trends is to repeat, on an annual or periodic basis, a sampling survey aimed at estimating total amounts. Double sampling with regression, which has been described, is an efficient method for these repeated surveys designed to keep track of trends. However, a few special considerations and some modifications of the previously described methods are required.

If a survey is to be conducted to follow the trend of an outbreak or evaluate the effectiveness of a control project, it is essential that it be started promptly. The first photography and plot establishment should be done after the first year's mortality shows up, if possible, and certainly no later than the second year. If the survey is delayed until after several years of mortality have occurred, it will be impossible to separate the total mortality into specific years *(14)*. Variation in the fading characteristics of dead trees will cause the photo interpreter to make frequent errors in dating the year of death, and even the field crews will not be able to make an accurate separation. However, if the survey is started promptly, the first year's mortality and that of each succeeding year can be separately estimated.

The basic method for double sampling with regression can be used on trend surveys. Locations for photo plots are chosen and photographs taken. Plot boundaries are laid out on the photos, and the number or volume of dead trees is determined. A subsample of these plots is chosen and visited in the field. The estimated total number or volume of dead trees is calculated by the method previously described. In

succeeding years, the same photo plots are rephotographed and the same field plots are revisited to determine the mortality that has occurred since the last survey.

Choosing an experienced contractor to do the aerial photography takes on added importance when trend surveys are made. Once the initial plot locations have been photographed, each succeeding year's photos must cover the same areas. If any of the initial plot locations are missed on later photos, they must be rephotographed. This is a difficult photography job, requiring an extremely competent pilot-photographer crew.

This problem of rephotographing the same locations several times is critical enough to warrant a modification in the previously described methods. After the initial grid of photo plots has been laid out on the base map, each of these locations should be carefully studied on prints from existing aerial photo projects. Certain of these plot locations will occur in dense uniform stands of timber with no visible features to pin down their position. It is impossible to rephotograph plots in such indeterminate locations. A solution to this predicament is to shift the location of such plots so that they fall near some prominent feature than can be seen from the air. A slight risk of bias is incurred here, but this seems preferable to the almost certain alternative that the original plot locations would be useless.

Interpretation of the first year's photos follows the same procedure previously described. However, for the following years, the interpreter has the advantage of being able to compare the current year's photos with those of the preceding year. Thus, when he spots a dead tree on the latest photos, he can check that same tree on last year's photos to see if it was already dead at that time or died in the last year. Failure to make this comparison is likely to result in so many interpretation errors that the photos lose their value *(14)*. The Old Delft scanning stereoscope is particularly useful for this comparison, for the two sets of photos can be arranged side by side. The interpreter can then switch back and forth betwen theem to make his comparisons. Identical grids laid over each plot help the interpreter to keep track of where he is as he jumps from one set of photos to the other.

The fieldwork on a trend survey is done in the manner previously described. Care should be taken that each tree tallied as mortality is prominently marked in the field, and it is desirable that the date of death be indicated. The computations for the regression double sample also proceed as previously described. When this type of survey is conducted for several years in a row, the annual estimates of mortality constitute a running account of the infestation progress which shows the trend taking place.

SALVAGE AND CONTROL OPERATIONS

Occasionally, insect outbreaks reach an epidemic level and kill or damage large amounts of valuable timber. If this timber is not harvested within a few years, it deteriorates rapidly and becomes relatively worthless. When such outbreaks occur, the land manager usually finds it an economic necessity to reorient his logging operations so that he can salvage as much of the dead timber as possible to minimize his losses. Moreover, rapid salvage sometimes helps to control the outbreak and minimize future losses.

An efficient salvage operation requires knowledge of the location of the dead timber. Finding and marking these trees on the ground is a slow and expensive process. Visual aerial observation is a good way to spot the general areas of mortality concentrations, but it is difficult to pinpoint the exact locations of the dead trees by this method. Aerial photography combines speed of coverage with pinpoint location ability and, in many situations, is the most efficient way of getting the information needed to plan and conduct salvage operations.

EVALUATING THE NEED FOR PHOTOGRAPHY

Usually, by the time a decision is reached to reorient logging operations for maximum salvage, the land manager has acquired a substantial knowledge of the amount and general locations of the dead timber. He probably has been made aware of the outbreak through reports from the field, or perhaps by a periodic aerial detection survey. In order to determine if there is enough dead timber to warrant reorganizing his logging plans, he has made at least a rough estimate of the amount through field checks, visual aerial reconnaissance, or perhaps by a double-sample survey as previously described. And, he has a pretty

good idea of where the biggest concentrations of mortality are, probably from an aerial reconnaissance.

In some cases, this may be all the information he needs to reorient his operations and concentrate on salvaging the maximum amount of dead timber. However, if he is still unsure as to which drainages contain the largest concentrations of dead trees, or if he suspects that the job of finding these concentrations and laying out settings is likely to be a slow and costly process on the ground, he should consider the possibility of expediting the job with aerial photographs. They may well save him more than their acquisition cost by minimizing the lost motion of hunting for dead trees and by speeding up the layout of logging roads and settings.

Before deciding to use aerial photos for this purpose, the land manager needs to make an assessment of the costs and benefits of this procedure in comparison with other alternatives. This involves many of the same considerations described for the regression double-sampling procedure, but the process is more subjective; it is not possible to calculate efficiency in this case. Among the factors to be considered are: size of area, accessibility, photo cost, nature of the damage or mortality, presence of complications, and obstacles to good photography.

OBTAINING PHOTOS

Aerial photos for salvage orientation must be obtained on a complete coverage rather than a sampling basis; otherwise, the considerations are quite similar to those previously discussed for double sampling with regression. One difference is that, if the area to be salvaged is larger than can be handled in one year, it should be divided into blocks. Then the block with highest priority can be photographed the first year, and the remaining blocks in succeeding years.

The spotting of individual dead trees and small groups can be done with more precision on color film than on panchromatic. However, medium- and large-size groups of dead trees usually can be easily

spotted on panchromatic film, especially if an orange filter has been used. If it is planned to make additional uses of the photos where panchromatic prints are preferable, this type of film is probably the best compromise.

Complete photographic coverage of high priority blocks is more expensive than scattered photo samples because of the large number of pictures needed to cover an area. But, by taking smaller scale photos than used to evaluate amounts of damage on sampling surveys, a compromise is made between accuracy and cost of photography. A reasonable compromise is a photo scale of approximately 1:7,920. Occasionally, one can use a smaller photo scale if dead trees are easily spotted. Such has been the case of newly faded groups of trees killed by the Douglas-fir beetle, or large areas of defoliator-killed trees. Group killing of this type can frequently be seen on 1:10,000 or 1:12,000 scale photos.

USING THE PHOTOS

Techniques for interpreting special photography on salvage operations are somewhat different from those previously described for sampling surveys because of the change in survey objectives. First, in-place information is needed on the dead timber that can be removed from a salvage area. Second, the most efficient manner of removing the distressed timber must be determined. Locating all visible mortality on the photos is the interpreter's job.

Locating Mortality

The interpreter examines in detail the photographs covering the salvage zone to pick out and mark on the photos all visibly dead trees. The locations and numbers of trees are transferred to a detailed base map.

Because of the large number of photographs to be handled, a simple method of coordinating photos and a base map should be planned. Usually the center point of each photo is located on a planimetric map, and all interpretation data are transferred from photos to map as needed. Standard photogrammetric techniques are used to maintain photo orientation between adjacent flight lines so that interpretation is not duplicated.

Photo interpreters frequently underestimate the number of trees in both large and small groups of mortality *(12)*. Because either a tree count or a volume estimate may be needed to establish priorities, the interpreter should also include a limited ground check. At least a few of the groups of dead or damaged trees should be ground checked for making the best estimate on number or volume of trees. This forms the basis for adjusting the photo estimate either by a flat factor or by a regression line.

Laying Out Roads and Settings

When the interpreter completes his delineation and estimation of tree mortality on the photos, data are transferred to a base map. This phase of the interpretation can well justify the expense of photography.

It is possible that the interpreter may be sufficiently experienced to do further photo analysis for road and settings selection, but generally the forester or engineer is responsible for this job.

Preliminary road locations and tentative settings are established from the photographs in relation to the mortality distribution. After review of the preliminary road layout and the amount and distribution of mortality, priorities are set for coordinating salvage and regular logging operation. Maximum use is made of existing and planned roads and settings to minimize disruption of current logging plans.

A logging setting for salvage is usually marked to include as much as possible of the beetle-killed timber, green timber infested with beetles, and salvable windfall or downed timber, along with a portion of green timber to make an economical setting. Rarely will a logging setting encompass all beetle-killed or infested timber. Some insect control benefits may be obtained by removing the maximum amount of beetle-infested timber during the logging operation.

Foresters have found that use of color photography implements the salvage job at a minimum cost. Usually it takes a forester 1 day in the field to lay out a single setting in the Douglas-fir type. With special color photography, the job takes about 20 minutes in the office. Volume estimates can also be made and checked in the field. Groundwork is much faster when crews navigate with the color photos rather than panchromatic photos in either dense or open stands.

CONTROL OPERATIONS

The job of controlling insect outbreaks involves several steps where aerial photographs might prove useful. Detailed procedures have not yet been worked out and tested. However, limited exploratory studies suggest some possible ways in which photos can increase the efficiency of a control project.

The effectiveness of the photographic approach is likely to vary substantially, depending on the type of insect being controlled. The greatest potentialities are with bark beetles that complete only one life cycle per year, such as the Douglas-fir and mountain pine beetles. A substantial percentage of the trees attacked by these insects fades a considerable time before the beetles emerge. Consequently, aerial photos can be used in surveys to estimate the number of beetle-infested trees, which indicates the size of the control operation needed. Such photos should also expedite the job of finding these trees on the ground and be useful in planning the control operations.

Photography for use in bark beetle control operations should be taken as late in the fall as weather permits. This gives infested trees a maximum chance to fade and be detected on the photos.

Special aerial photos are not likely to be helpful in control projects for the various defoliators or bark beetles, such as the western pine beetle, which have several generations a year. By the time the damage shows up on the photos, the insects have left the trees. However, if panchromatic photos at scales from 1:12,000 to 1:20,000 are available, they are useful as detailed map substitutes for guiding the control operations.

In the planning stages of a bark beetle control project, some idea of the number of currently infested trees is usually desired. It is possible that aerial photos, used in a scheme of double sampling with regression, will prove useful for this purpose. Aerial photos for this purpose are best taken in the late fall or winter after the maximum number of trees attacked the preceding spring and summer have faded. On the large photo plot sample, the visibly faded trees would be counted. A sub-sample of these plots would be visited in the field, and the numbers of infested trees, green as well as faded, would be counted. If the coefficient of correlation between the photo counts of faded trees and the field counts of infested trees is sufficiently high, this approach will produce a better estimate of the infested tree numbers than a straight field survey of equal cost.

Complete photo coverage of the control project area may help to minimize the field job of finding, marking, and treating or harvesting the infested trees. Using aerial photos will not eliminate the chore of searching the entire control area on the ground, for many of the infested trees will still be green and therefore cannot be detected on the photos. However, the photos will reveal concentrations of faded trees, and the green infested trees will often be found concentrated in the same areas. It seems doubtful that the savings in field time for this purpose alone will pay the cost of special aerial color photography. However, if the photos are used to help estimate the number of infested trees requiring control and the volume of dead timber available for salvage, then used to aid in finding and marking the infested trees, and finally used to plan and execute salvage and control operations, it seems likely that their cost will be more than recovered.

MODIFICATIONS FOR SPECIFIC INSECT PROBLEMS

The foregoing sections have described the general principles and step-by-step methods recommended for using aerial photos to estimate amounts of damage or mortality caused by forest insects. They have also presented some recommendations for using aerial photographs in planning and orienting salvage and control operations. Two additional questions need to be considered: To what specific insect and host tree species do these procedures apply? What exceptions are there to the generalized methods?

Answers to these questions must be based on experience from studies and operational surveys on a limited number of insect and tree species combinations. These are covered in the following discussion. There remain, however, a great many insect and tree combinations for which the survey capability of aerial photos is unknown. The forester, faced with a survey problem in one of these situations, will have to judge the possible usefulness of photos by studying the survey procedures in the light of his knowledge of how the insect behaves and how the damage appears in the trees.

The basic principles and procedures have been described generally without reference to specific insect or tree species, though occasionally some have been named as examples. The general approach and step-by-step procedures for using aerial photos in forest insect surveys is the same, regardless of the species involved. In some of the details, however, specific insect and tree combinations require departures from the general recommendations. These departures affect only certain phases of the methodology: size and shape of plot, film type, photo scale, timing of the survey, and complicating factors to watch out for.

What is known about plot size and shape under specific forest conditions has already been covered in the section entitled "Size and

Shape of Plot." The following discussion on specific insects presents suggestions for certain departures from the general recommendations on film, scale, timing, and complicating factors. Where departures are not suggested, the reader should assume that the general recommendations apply.

DOUGLAS-FIR BEETLE

Large-scale aerial color photographs have proved useful for evaluating Douglas-fir mortality caused by epidemics of the Douglas-fir beetle, *Dendroctonus pseudotsugae* (Hopk.), in studies, pilot-plant tests, and operational surveys conducted in western Oregon *(12, 13, 14)*. Another study in southwestern Oregon indicated that such photos were a valuable aid in planning and orienting salvage of the dead timber *(7, 13)*.

Mortality caused by Douglas-fir beetle outbreaks is probably easier to detect and identify on aerial photographs than any other kind of insect-caused damage. Much of the mortality tends to occur in large groups, and even small clumps of dead trees stand out amidst the typically dense even-aged canopy of west-side forests. Moreover, in these areas there are seldom any complicating factors causing mortality that could be confused with that of the Douglas-fir. For these reasons, heavy damage generally shows up well on 1:12,000-scale panchromatic photos, especially when an orange or red filter has been used. Thus, in a situation where additional uses for new photography are planned and where the best type is 1:12,000-scale panchromatic, such photography should also prove useful for evaluating mortality amounts and orienting salvage operations.

Where mortality evaluation or salvage orientation are the sole objectives, large-scale color photos should more than pay for their extra cost. It is generally not necessary to strive for the largest possible scale as it is for most insect damage. Sample plots can be photographed at 1:5,000 or 1:6,000 scale, and complete coverage for salvage or control orientation can be taken at scales of 1:8,000 to 1:10,000.

Although aerial photographs have not been tested in the Douglas-fir types of eastern Washington and Oregon, it seems likely that the detection and identification of mortality caused by the Douglas-fir beetle would be more difficult here. The stands tend to be more open, and there are often other species mixed in. Mortality in some of the true firs or in ponderosa pine might be confused with that of the Douglas-fir. Under these conditions, it would seem best to stick to the generalized recommendations of using color film rather than panchromatic and using the largest possible scale for photographing sample plots.

WESTERN PINE BEETLE

Several studies in northern California and eastern Oregon have tested the use of aerial photographs for evaluating ponderosa pine mortality caused by the epidemics of the western pine beetle, *Dendroctonus brevicomis* (Lec.). The results indicated that special aerial color photos will more than pay their way when used in double-sample surveys to estimate mortality amounts. Similar results were obtained for Coulter pine mortality in a southern California study. Aerial color photos have also proved useful aids in planning and orienting salvage and control operations in eastern Oregon *(4)*.

Ponderosa pine trees killed by the western pine beetle are not as easy to detect and identify on aerial photos as is the mortality caused by the Douglas-fir beetle. There are several reasons for this.

A greater proportion of the mortality occurs as single trees and small groups which are harder to spot than large groups. In the typically open-grown ponderosa pine stands, much of the ground is visible; and it often appears reddish or yellowish on color photos, either because of the nature of the soil or from the dead needles on the surface. The faded crowns of dead and dying trees are often difficult to detect against this background. Moreover, the western pine beetle often attacks some trees several times before finally killing them. Such trees usually die progressively from the top down and, when finally dead, have the appearance of much older mortality.

Identification of ponderosa pine mortality caused by the western pine beetle is sometimes complicated by the presence of mortality caused by other agents, either in the pine or in some of the associated species. *Ips* beetles frequently cause topkilling in ponderosa pine, and some of the flatheaded borers cause topkilling or tree mortality. Intermingled Douglas-fir killed by the Douglas-fir beetle is often hard to distinguish from ponderosa pine mortality. The two species have similar shades of yellow, orange, and red when they fade, and often their crown shapes are similar. On the other hand, dying white fir, which is frequently mixed with the ponderosa pine, is usually not a problem. White fir crown shape is fairly easy to distinguish from that of pine, and it fades to a pink or rosy red rather than orange or rust color.

Another occasional source of confusion in inventorying ponderosa pine mortality is a recent ground fire which has run through the area irregularly, killing a few trees here and there. On the photos, this spotty mortality may have the appearance of beetle-killed trees. A check of fire records should alert the interpreter to this possible source of error.

Because of these various sources of mortality that could be confused with beetle-killed ponderosa pine trees, it is important that some field checking be done before undertaking a survey. If much of this extraneous mortality is present, aerial photographs are likely to be useful only for estimating total mortality from all causes. If the survey objective is to estimate the amount of ponderosa pine killed by the western pine beetle, a straight field survey is likely to be more efficient.

Studies have indicated that panchromatic photography cannot be depended upon for surveys of ponderosa pine mortality; one of the color films should be used. Sample plot photography should be at the largest practicable scale, which is about 1:4,000. However, when obtaining complete coverage for use in salvage operations, a scale of approximately 1:8,000 is recommended.

ENGELMANN SPRUCE BEETLE

One study was made in Colorado to test the use of aerial photos to evaluate Engelmann spruce mortality caused by the Engelmann spruce beetle, *Dendroctonus obesus* (Mann.). Large-scale color photos were used, but the dead spruce trees could not be identified with sufficient precision to be useful.

The fading characteristics of Engelmann spruce and complications caused by other mortality contributed to the difficulty of using aerial photos for this purpose. The rate of fade varies considerably from tree to tree, and often does not occur until a year after attack. Then the needles may fall without changing color, or may merely turn light green before falling.

Moreover, lodgepole pine, which is typically mixed with the spruce, often suffers mortality at the same time as the spruce. And it is difficult to distinguish between the two species, even at large photo scales.

At present, aerial photos cannot be recommended for surveys of Engelmann spruce mortality.

BALSAM WOOLLY APHID

Aerial color photography has been successfully used on inventories of damage and mortality caused by the balsam woolly aphid, *Adelges piceae* (Ratz.), in southwestern Washington *(6)* and in western Oregon.

The damage is relatively easy to detect and identify on large-scale color photos, and is especially striking on Ektachrome Infrared film (fig. 3). Pacific silver fir and subalpine fir, the preferred host trees, are easy to identify by their distinctive crown shapes. Moreover, the damage typically starts at the top of the crown and progresses downward. Thus, it is visible from the aerial viewpoint, and it is even possible to do a reasonable job of estimating tree damage classes from aerial

photos. The damage shows up best in the period from late July to early September.

In past surveys employing aerial photos, there has not been any other damage or mortality which could be confused with that caused by the balsam woolly aphid. However, there have been outbreaks of silver fir mortality caused by a combination of silver fir beetles and armillaria root rot. If these should occur at the same time and place as a balsam woolly aphid epidemic, separation of the two types of damage would probably be impossible.

OTHER INSECTS

Little else is known about the use of aerial photographs in surveying damage caused by other insects in the West. Color photos at a scale of 1:3,000 were taken of trees damaged by western hemlock looper, *Lambdina fiscellaria lugubrosa* (Hulst). Where damage was heavy or very heavy, it could be detected; but the light to moderate damage was principally in the lower part of the crowns and could not be seen.

Large-scale aerial color photos have been tested with some success on damage caused by the spruce budworm, *Choristoneura fumiferana* (Clem.). However, visual aerial observation was found to give a more efficient assessment of damage intensity classes *(8)*.

Damage caused by defoliators is generally difficult to detect on 1:12,000-scale aerial photos unless it is extremely heavy. Very large photo scales (1:500 or 1:1,000) might show light damage; but such scales require special cameras and the small ground area covered makes the plots difficult to field check. At present, aerial photos are not recommended for defoliator damage surveys.

There are undoubtedly additional insect and tree species combinations for which damage can be successfully inventoried with the help of aerial photos. Armed with a knowledge of the insects' habits, the fading pattern of the host tree, and the basic principles of using aerial

photos, it should be possible to judge how useful photos might be in a situation which has not been tested. It is important to keep in mind the two chief requirements for successful application of aerial photos: (1) damage distinct and visible from the aerial viewpoint and (2) absence of significant amounts of additional damage in other species, or from other sources, which could be confused with the damage being inventoried.

An example of a situation where aerial photos should prove useful is mortality caused by the mountain pine beetle, *Dendroctonus ponderosae* Hopk., to lodgepole pine stands or immature stands of ponderosa pine (fig. 3C). When this insect is epidemic, it tends to kill large groups of trees which fade in bright colors and should be easily detected on color photos.

Since trees in the attacked stands tend to be small, the largest possible photo scale would seem desirable. For sample plots, a scale of about 1:3,000 should be appropriate; but complete coverage for salvage operations should probably be from 1:6,000 to 1:8,000.

As with all surveys of this type, some field checking should be done to make sure that no other source of confusion is present. The mountain pine beetle may attack other pines and even fir, spruce, and hemlock, if present.

LITERATURE CITED

(1) AMERICAN SOCIETY OF PHOTOGRAMMETRY.
1965. Manual of photogrammetry. Ed. 3, 1220 pp., illus. Menasha, Wis.: George Banta Publishing Co.

(2) ....
1960. Manual of photographic interpretation. 868 pp., illus. Menasha, Wis.: George Banta Publishing Co.

(3) COCHRAN, W. G.
1963. Sampling techniques. Ed. 2, 413 pp. New York: John Wiley & Sons, Inc.

(4) DOLPH, ROBERT E., JR., AND WEAR, JOHN F.
1963. A survey of western pine beetle damage on the Fremont National Forest using color photographs. U.S. Forest Serv. Pacific Northwest Region, 9 pp., illus.

(5) FREESE, FRANK.
1962. Elementary forest sampling. U.S. Dep. Agr. Handb. 232, 91 pp.

(6) POPE, ROBERT B.
1958. Final report, cooperative evaluation survey of Chermes damage, Mount St. Helens, Washington, 1957. U.S. Forest Serv. Pacific Northwest Forest & Range Exp. Sta., 25 pp.

(7) SMYTH, ARTHUR V.
1959. The Douglas-fir bark beetle epidemic on the Millicoma Forest: methods used for control and salvage. J. Forest. 57:278-280, illus.

(8) WATERS, W. E., HELLER, R. C., AND BEAN, J. L.
1958. Aerial appraisal of damage by the spruce budworm. J. Forest. 56:269-276, illus.

(9) WEAR, J. F.
1960. Interpretation methods and field use of aerial color photos. Photogram. Eng. 26:805-808, illus.

(10) .... AND BONGBERG, J. W.
1951. Uses of aerial photographs in control of forest insects. J. Forest. 49:632-633.

(11) .... AND BUCKHORN, W. J.
1955. Organization and conduct of forest insect aerial surveys in Oregon and Washington. U.S. Forest Serv. Pacific Northwest Forest & Range Exp. Sta., 41 pp., illus.

(12) .... AND DILWORTH, J. R.
1955. Color photos aid salvage of beetle-killed Douglas fir timber as mapping technique is developed. The Lumberman 82(13):88-89; 132-133, illus.

(13) .... AND LAUTERBACH, P. G.
1956. Color photographs useful in evaluating mortality of Douglas-fir. Soc. Amer. Forest. Proc. 1955:169-171.

(14) ...., POPE, R. B., AND LAUTERBACH, P. G.
1964. Estimating beetle-killed Douglas-fir by aerial photo and field plots. J. Forest. 62:309-315.

SUGGESTED REFERENCES

BECKING, RUDOLF W.

1959. Forestry applications of aerial color photography. Photogram. Eng. 25:559-565.

COLWELL, ROBERT N.

1950. New technique for interpreting aerial color photography. J. Forest. 48:204-205.

....

1954. A systematic analysis of some factors affecting photographic interpretation. Photogram. Eng. 20:433-454, illus.

....

1956. Determining the prevalence of certain cereal crop diseases by means of aerial photography. Hilgardia 26:223-286, illus.

....

1960. Some uses and limitations of aerial color photography in agriculture. Photogram. Eng. 26:220-222.

....

1960. Aerial photography — a valuable sensor for the scientist. Amer. Sci. 52 (1):16-49, illus.

HELLER, R. C., ALDRICH, R. C., AND BAILEY, W. F.

1959. An evaluation of aerial photography for detecting southern pine beetle damage. Photogram. Eng. 25:595-606, illus.

........................, DOVERSPIKE, G. E., AND ALDRICH, R. C.

1964. Identification of tree species on large-scale panchromatic and color aerial photographs. U.S. Dep. Agr. Handb. 261, 17 pp., illus.

HELLER, ROBERT C., ALDRICH, ROBERT C., AND BAILEY, W. F.

1959. Evaluation of several camera systems for sampling forest insect damage at low altitude. Photogram. Eng. 25:137-144, illus.

JOHNSON, EVERT W.
1954. Role of aircraft in forest-pest control. Sci. Mon. 79:379-391, illus.

KEEN, F. P.
1952. Insect enemies of western forests. U.S. Dep. Agr. Misc. Pub. 273 (rev.), 280 pp. illus.

KNIGHT, FRED B.
1958. Methods of surveying infestation of the Black Hills beetle in ponderosa pine. Forest Sci. 4:35-41.

LANGLEY, PHILIP G.
1959. Aerial photography as an aid in insect control in western pine and mixed conifer forests. J. Forest. 57:169-172.

LOSEE, S. T. B.
1951. Photographic tone in forest interpretation. Photogram. Eng. 17:785-799, illus.

....
1953. Timber estimates from large-scale photographs. Photogram. Eng. 19:752-762.

MILLER, J. M., AND KEEN, F. P.
1960. Biology and control of the western pine beetle. U.S. Dep. Agr. Misc. Pub. 800, 381 pp., illus.

O'NEILL, HUGH, AND NAGEL, WILLIAM.
1952. The O'Neill-Nagel light-table (a multipurpose light-table) its uses in photo-interpretation of color and other photography. Photogram. Eng. 18:134-139, illus.

SISAM, J .W. B.
1947. The use of aerial survey in forestry and agriculture. Great Brit. Imp. Forest. Bur. Joint Pub. 9, 59 pp., illus.

SMITH, JOHN T., JR.
1963. Color — a new dimension in photogrammetry. Photogram. Eng. 29:999-1013, illus.

SPURR, STEPHEN H.

1948. Aerial photographs in forestry. New York: The Ronald Press Co. 340 pp., illus.

TARKINGTON, RAIFE G., AND SOREM, ALLAN L.

1963. Color and false-color films for aerial photography. Photogram. Eng. 29:88-95, illus.

U. S. FOREST SERVICE.

1953. Operations manual 1953 blowdown-bark-beetle survey. U.S. Forest Serv. Pacific Northwest Forest & Range Exp. Sta., 9 pp., plus illus.